An Instrumentation Wish List
for
High Power/High Brightness ERLs

D. Douglas, JLab

Abstract

The advent of the energy recovering linac (ERL) brings with it the promise of linac-quality beams generated with near storage ring efficiency. This potential will not, however, be fulfilled without overcoming a number of technical and operational challenges. We will review the basics of ERL dynamics and operation, and give examples of idiosyncratic ERL behavior and requirements posing particular challenges from the perspective of diagnostics and instrumentation. Beam performance parameters anticipated in next-generation ERLs will be discussed, and a "wish list" for the instrumentation of these machines presented.

What are ERLs?

Compare to conventional accelerators…

- Rings
  - Recycle each accelerated particle an infinite number of times – adding a bit of energy each time
  - High beam powers for modest input power: ***efficient acceleration***
    - MW of RF + MW DC ⇒ GW beam power (e.g., 0.5 A @ 2 GeV)
  - Circulation of beam ⇒ radiation excitation ⇒ inherently ***limited beam quality***

- Linacs
  - Accelerate each particle rapidly in a multiple RF structures
  - Beam power inherently less than power required for acceleration (wall losses): ***inefficient acceleration***
    - MW of RF + MW of DC ⇒ MW beam power (e.g., 50 μA @ 20 GeV)
  - *BUT*… Beam is not in machine long enough for quality to degrade: ***performance is source limited***

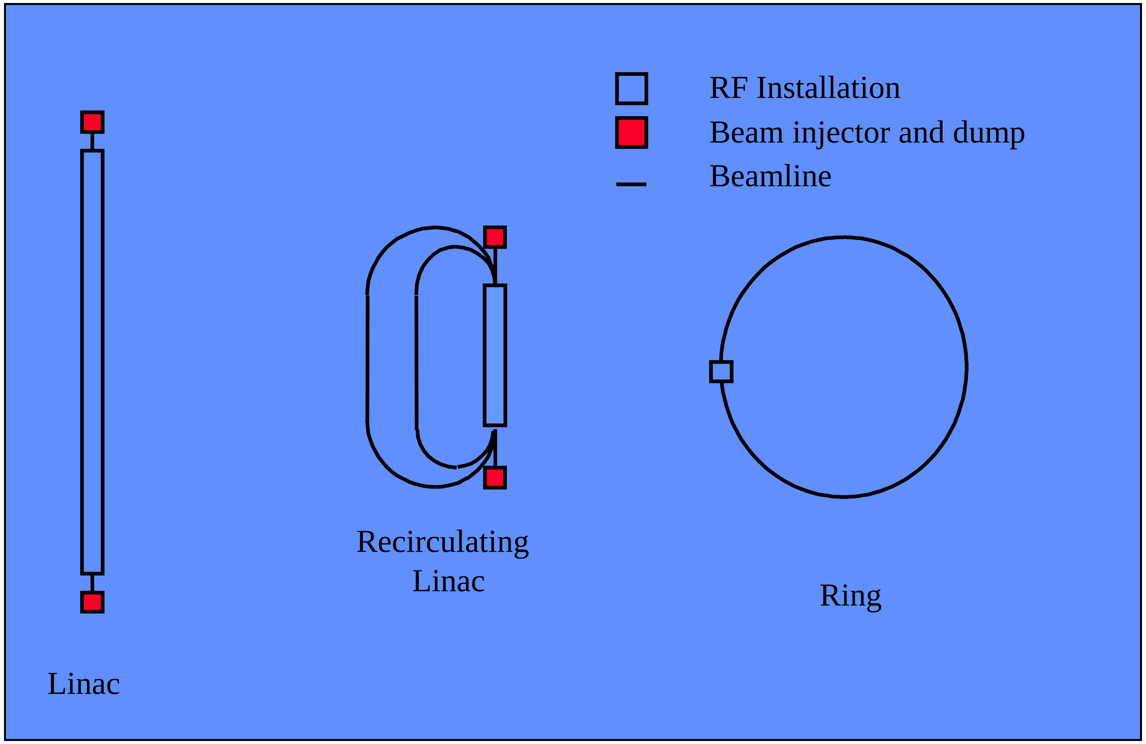
Linac Cost/Performance Optimization: *Recirculation and SRF*

Linacs provide great beam quality, so its worthwhile to try to make them more cost effective

To control cost & improve performance, linac builders utilize certain "slight of hand" tricks

- ***Recirculation*** : "reuse" accelerating structure, reducing linac size and hence cost
  - Transport beam from end of linac & reinject in phase with the RF fields for further acceleration
- ***Superconducting RF*** : avoids wall losses
  - Allows high gradient CW operation
  - Dramatically reduces required RF power (enough to offset cost of cryogenic plant and additional RF system complexity)
  - Significantly improves beam quality

Machine Topologies



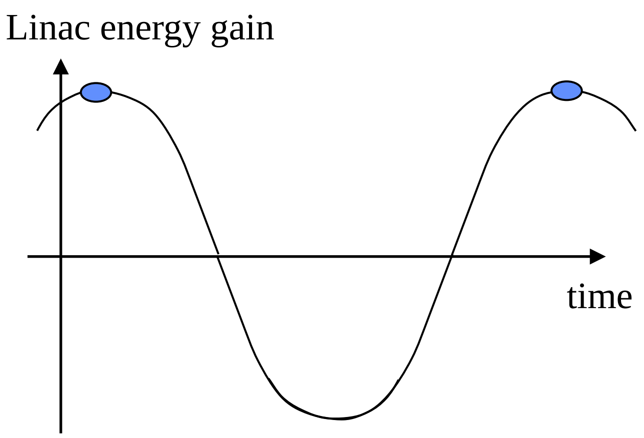
Whence ERLs?

- Use of recirculation reduces cost
  - Beamline inexpensive relative to RF
- Proper system design avoids instabilities, beam quality degradation
- ***RF power still a problem:***
  - CEBAF: 200 μA x 4 GeV = 0.8 MW
    - manageable (affordable)
  - Light source 100 mA x 5 GeV = ½ GW
    - needs dedicated nuclear power plant...
    - and… what do you do with a GW of waste electrons?

The Next Step: Energy Recovery

So, "consider a circular linac"… or at least a recirculated linac

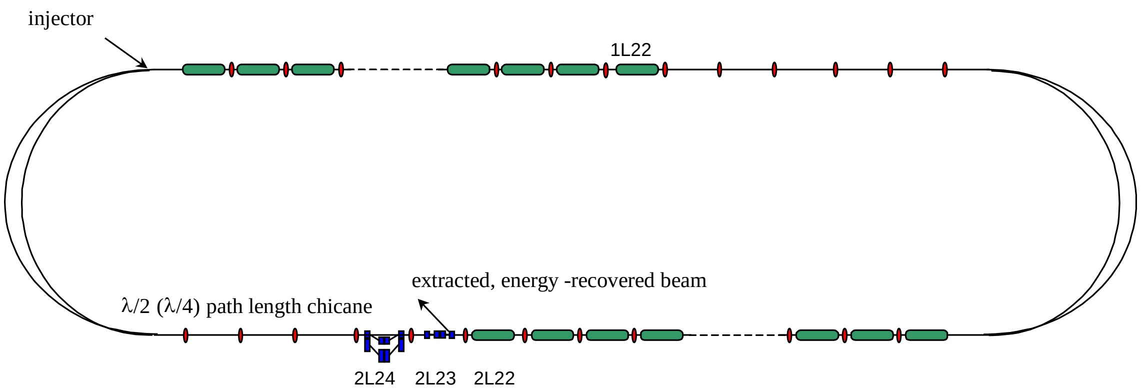
- To accelerate turn-to-turn, beam bunches must be synchronous with RF. Pass-to-pass phase is important!
- You might wonder what will happen if you reinject the beam out of phase with the accelerating field, rather than in phase…

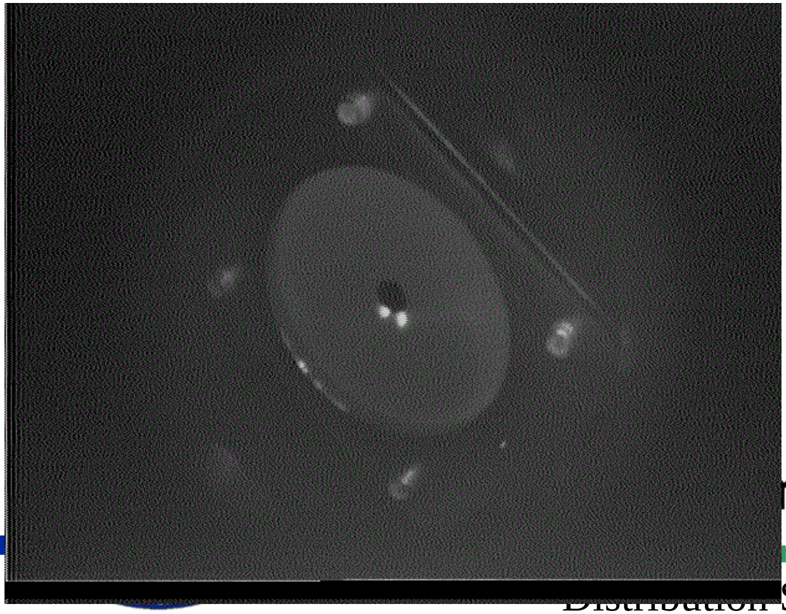


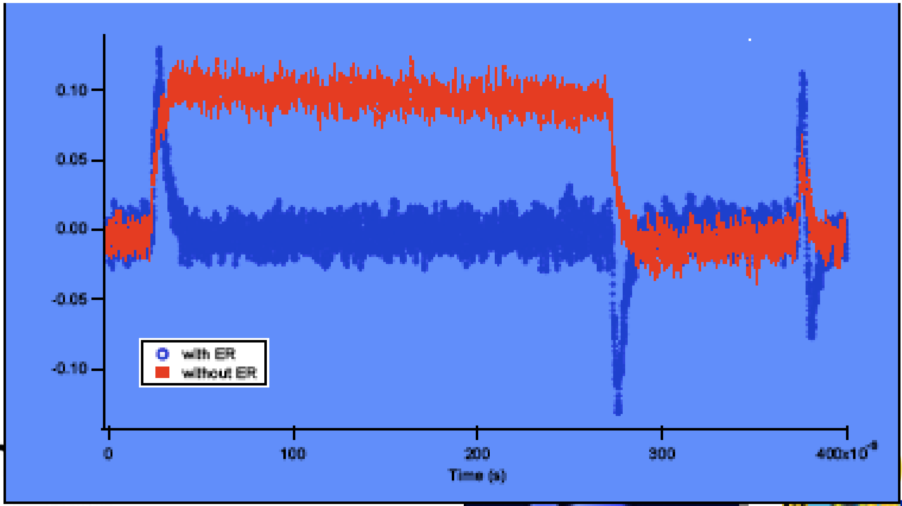
Subsequent pass is *decelerated* – the beam power is deposited back into the RF system…

and can be used to accelerate later bunches!

Example: CEBAF-ER







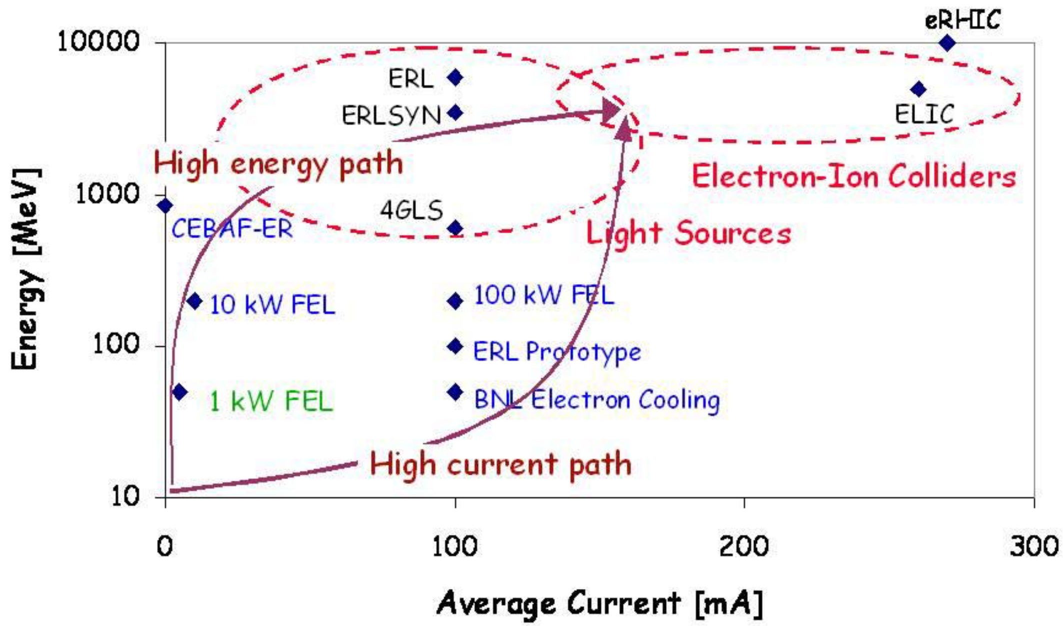
Why are ERLs?

- ***IMPROVED EFFICIENCY OF ACCELERATION***
  - SRF ⇒ no wall losses
  - Energy recovery ⇒ "no" beam loading - ***Only injected beam power is needed***
    - Inject 0.1 A @ 10 MeV (1 MW), accel. to 100 MeV (10 MW), & recover:***1 MW***
    - Inject 0.1 A @ 10 MeV, (1 MW) accel. to 10 GeV (10 GW), & recover: ***1 MW***
  - Recycle "waste" (post-use) beam to drive RF
    - Save on RF costs, dumped radiation
    - A natural "two beam accelerator"
- ***Near-linac beam quality at near-storage ring efficiency***
  - Cost optimization
  - "Recovered" beam is at low energy/low POWER; beam dump easier
- ***Entertainment value***
  - Numerous phenomena (source limitations, space charge, BBU, CSR, halo) become of interest

ERL Performance

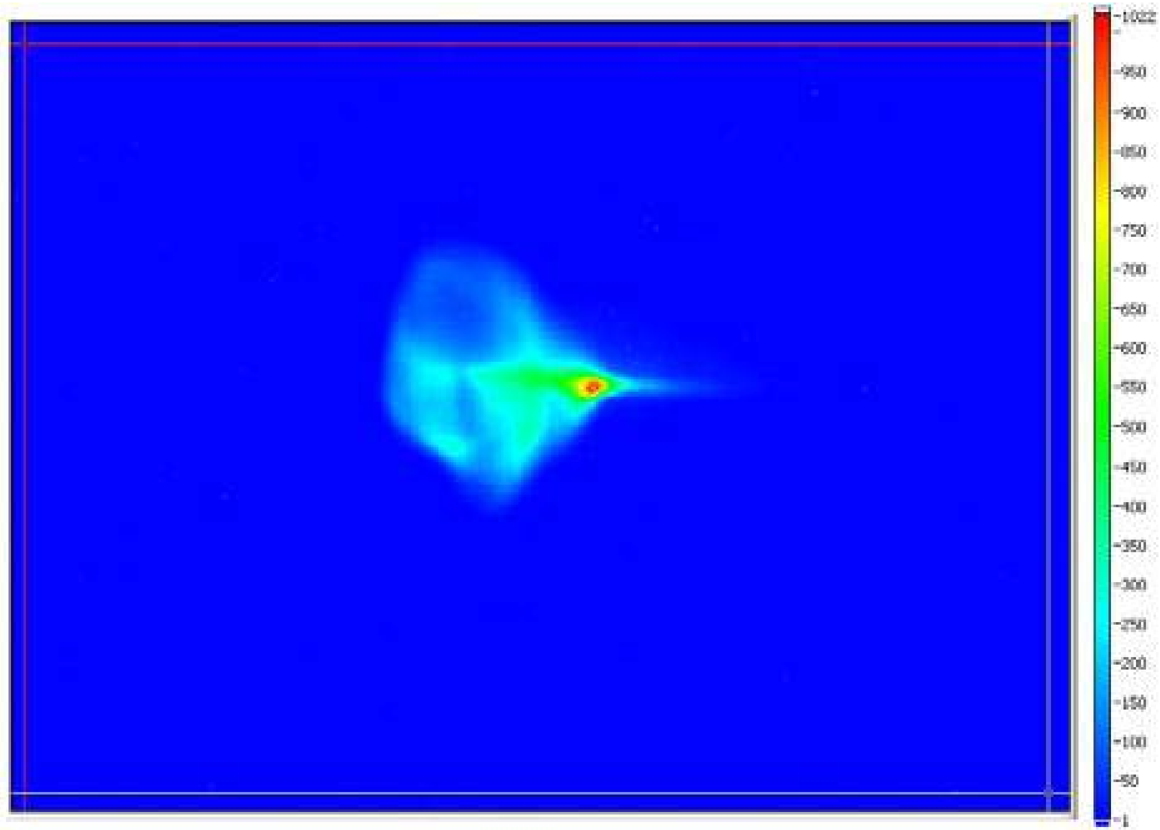
ERLs provide very high power/high brightness beams

- FEL drivers
  - E: 10s of MeV – few GeV
  - Q: 100s pC – 1 nC
  - I: mA – 10s mA
  - $\varepsilon^{normalized} \sim \lambda/4\pi$
    - 1-10 mm-mrad
  - $P_{beam} \sim$ MW
- Light sources
  - E: 5 – 10 GeV
  - Q: ~10s pC – 100 pC
  - I: 100(s) mA
  - $\varepsilon^{normalized} < \sim 1$ mm-mrad
  - $P_{beam} \sim$ GW



- ***high power=> halo major issue! Can't lose 10^{-5} of beam!
- implications: tiny spot size, COTR effects, 6-d systems…

Linac beams do not occur in distributions named after dead mathematicians… (P. O’Shea)



courtesy
P. Evtushenko

but they do look like hummingbirds

But wait, there's more… "*How*" Are ERLS?

*That is – how do they **work**, and how do you **use** them?*

- Its fun to accelerate/decelerate a beam, but you're not likely to get funded to do that unless you plan to *use* it for something…
- At some point – logically, full energy – the beam interacts with a target, makes light, *something*, which typically
  - Takes energy out
  - Degrades the phase space
- As a result, ERL operation is not just a matter of riding the RF crest up and RF trough back down…

ERLs Provide Advantages over Traditional Machines

- Provide linac quality beam, with near storage ring power (energy & current) with wall-plug efficiencies approaching that of storage rings…
- Allow flexible time structure, from single bunch to CW bunch train, and everything in between (w/i constraints of the source)
- Allow independent manipulation of various portions of phase space essentially at will and independently of other sub-spaces – they are fully 6 dimensional systems!
  - Transverse matching to desired spot sizes
  - Longitudinal matching to desired bunch length/energy spread (transverse longitudinal coupling)
  - H/V coupling – phase space exchange

ERLs Have Unique Properties

- Do not have a closed orbit
- Do not go to quantum equilibrium (beam in machine<<damping/excitation time)
- Are not necessarily betatron stable
  - Might therefore not have uniquely defined Twiss parameters
  - Beam and lattice are *not* the same – cannot identify Twiss parameters, betatron functions, lattice functions as "the same" (in contrast to ring at equilbrium)
- Have multiple beams (at least 2, maybe 4, 6, 8, ….) in different focusing/accelerating structures – while they are physically *in the same devices*
  - Different passes through linac can be phased &/or focus differently depending on energy
    - Example (show below) : multipass orbit correction (w/o BPMs ☹)
- Engage in all manner of longitudinal manipulations to compress bunch in duration and/or energy
  - Example: FEL driver longitudinal match (show below)
- Topology more like storage ring than linac => allow feedback/feed-forward more easily than in linac

ERL Challenges

- Sit in a strange place in parameter space & provide none of the advantages of storage rings and linacs while being susceptible to all their problems and costing twice as much as either…(?!?)
  - "the last millenium's solution to this millenium's problem at the next millenium's prices"
- Very bright, high power beams => many phenomena are relevant
  - Beam interacts with itself
    - LSC, CSR, MBI
  - Beam interacts with environment
    - BBU, Resistive wall, Environmental wakes/impedances of all kinds…
    - COTR
  - Stray power deposition
    - Propagating HOMs, CSR/THz, Halo,…
  - effect of field errors
    - transverse/longitudinal coupling; $\Delta B/B \Rightarrow \delta E/E$

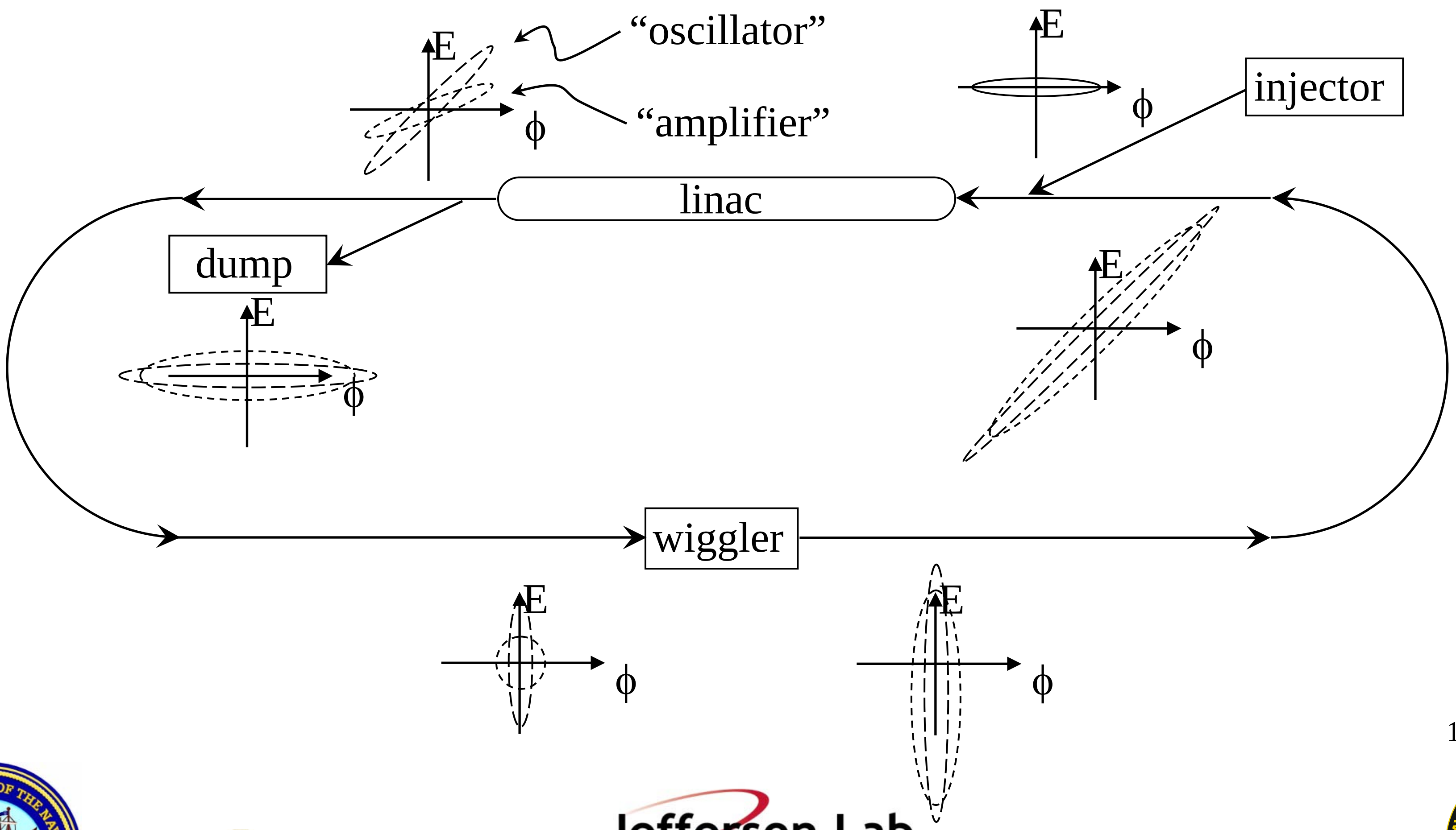
Typical ERL Idiosyncrasies

Examples intended to provide insight on the kinds of issues driving diagnostic requirements…

1. Nonlinear longitudinal matching
2. Multipass orbit correction
3. Collective Effects
    - LSC, BBU, CSR
4. Transverse/longitudinal coupling
    - magnetic field errors => energy errors

Example 1: Longitudinal Matching in an ERL

Schematic Longitudinal Matching for ERL-Driven FEL



Energy Recovery: Details

ERL operational experience has shown how to successfully energy recover; this has implications on system efficiency

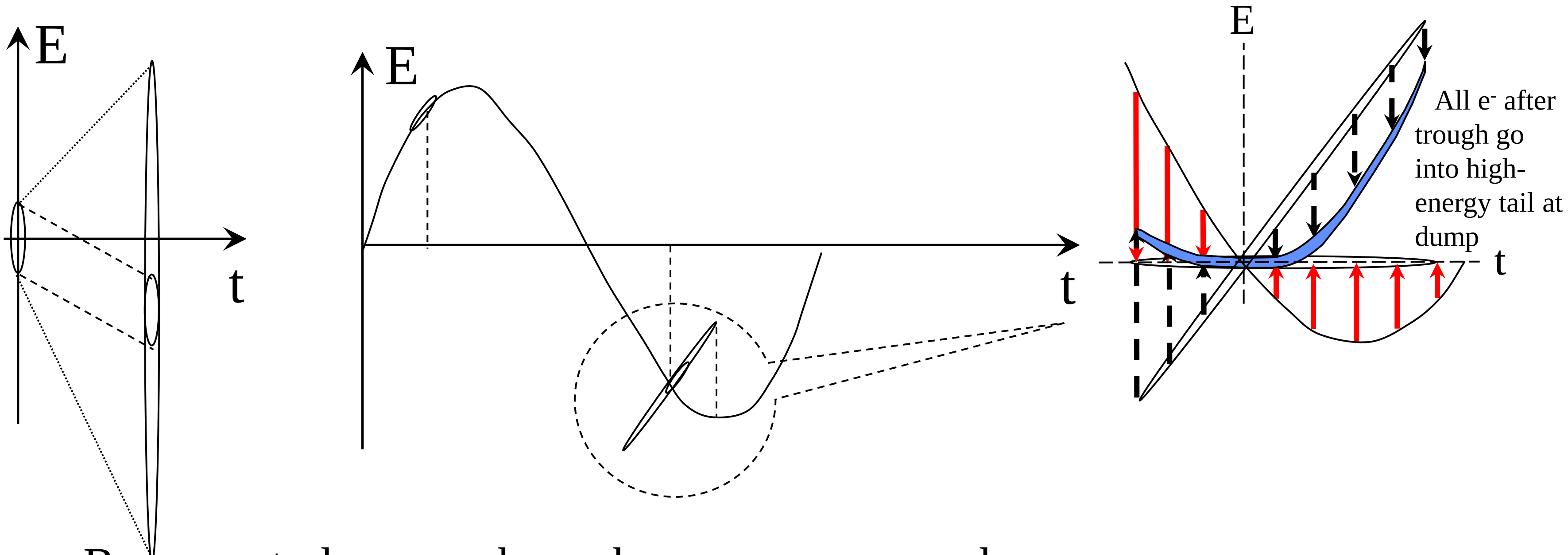
Longitudinal Match to Wiggler

- Inject long, low-energy-spread bunch to avoid LSC problems
  - need 1-1.5^{o} rms with 1497 MHz RF @ 135 pC in our machine
- Chirp on the rising part of the RF waveform
  - counteracts LSC
  - phase set-point then determined by required momentum spread at wiggler
- Compress (to required order, including curvature/torsion compensation) using recirculator compactions M_{56}, T_{566}, W_{5666},…
- Entire process generates a parallel-to-point longitudinal image from injector to wiggler

Longitudinal Match to Dump

- FEL exhaust bunch is short & has very large energy spread (10-15%)
- => Must energy compress during energy recovery to avoid beam loss linac during energy recovery; this defines the longitudinal match to dump
  - Highest energy must be phase-synchronous with (or precede) trough of RF wave-form
  - Transport momentum compactions must match the slope (M_{56}), curvature (T_{566}), torsion (W_{5666}),… of the RF waveform
- Recovered bunch centroid usually *not* 180^{o} out of phase with accelerated centroid
  - Not all RF power recovered, but get as close as possible (recover ahead of trough), *because*…
  - Additional forward RF power required for field control, acceleration, FEL operation; more power needed for larger phase misalignments
- For specific longitudinal match, energy & energy spread at dump does not depend on lasing efficiency, exhaust energy, or exhaust energy spread
  - Only temporal centroid and bunch length change as lasing conditions change
- The match constitutes a point-to-parallel image from wiggler to dump

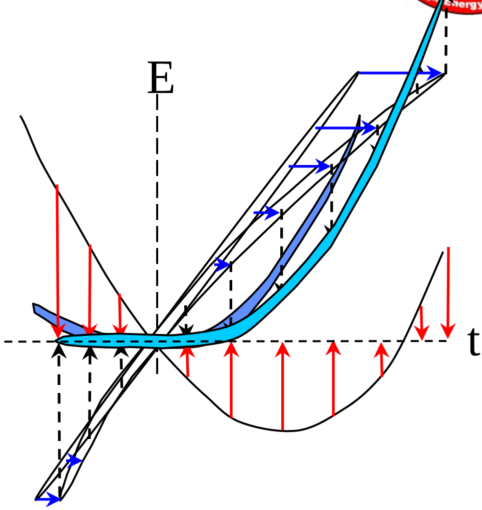
Energy Compression



- Beam central energy drops, beam energy spread grows
- Recirculator energy must be matched to beam central energy to maximize acceptance
- Beam rotated, curved, torqued to match shape of RF waveform
- Maximum energy can’t exceed peak *deceleration* available from linac
    - Corollary: entire bunch must precede trough of RF waveform

Higher Order Corrections

- Without nonlinear corrections, phase space becomes distorted during deceleration
- Curvature, torsion,… can be compensated by nonlinear adjustments
  - differentially move phase space regions to match gradiant required for energy compression
- Required phase bite is $\cos^{-1}(1-\otimes E_{FEL}/E)$; this is >25° at the RF fundamental for 10% exhaust energy spread, >30° for 15%
  - typically need 3rd order corrections (octupoles)
  - also need a few extra degrees for tails, phase errors & drifts, irreproducible & varying path lengths, etc, so that system operates reliably
- In this context, harmonic RF very hard to use…



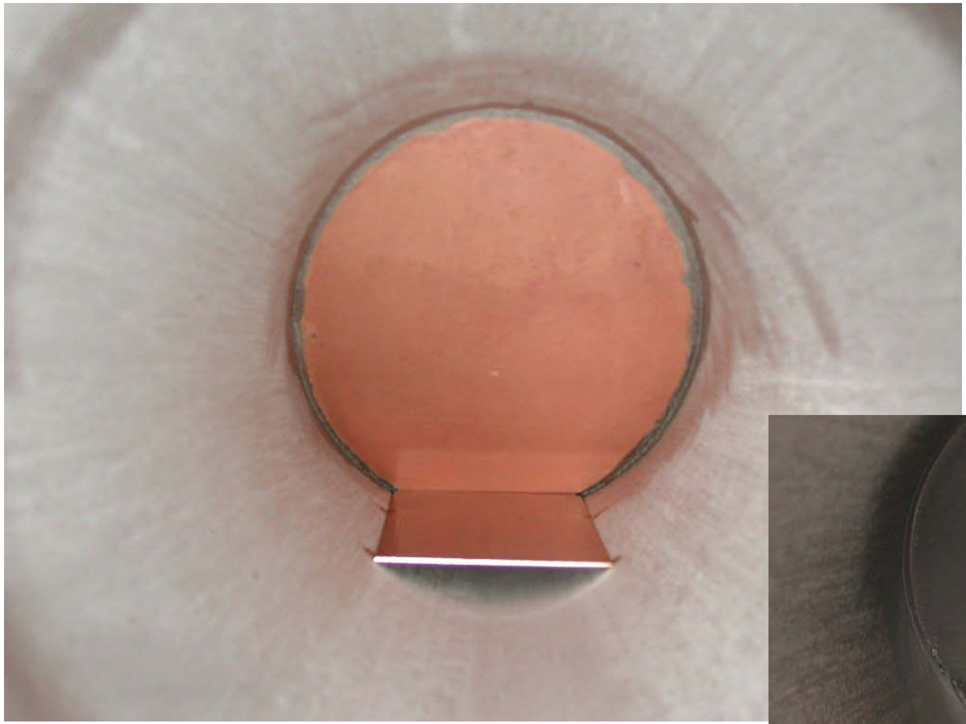
$$M_{56} = -\frac{\lambda_{RF}}{2\pi}\left(\frac{E_0}{E_{linac}}\right)\frac{1}{\sin\phi_0}$$

$$T_{566} = -\frac{1}{2}\left(\frac{2\pi}{\lambda_{RF}}\right)(M_{56})^2\frac{\cos\phi_0}{\sin\phi_0}$$

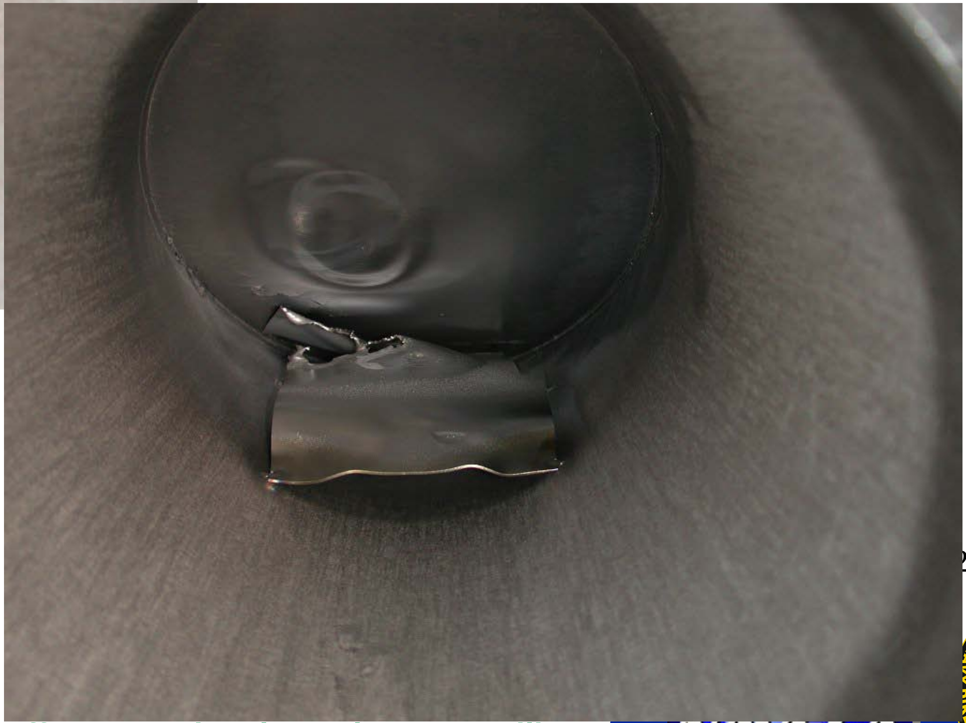
$$W_{5666} = -\left[\frac{1}{6}+\frac{1}{2}\frac{\cos^2\phi_0}{\sin^2\phi_0}\right]\left(\frac{2\pi}{\lambda_{RF}}\right)^2(M_{56})^3$$

$$U_{56666} \propto \left(\frac{2\pi}{\lambda_{RF}}\right)^3(M_{56})^4\text{, etc.}$$

JLab IR Demo Dump



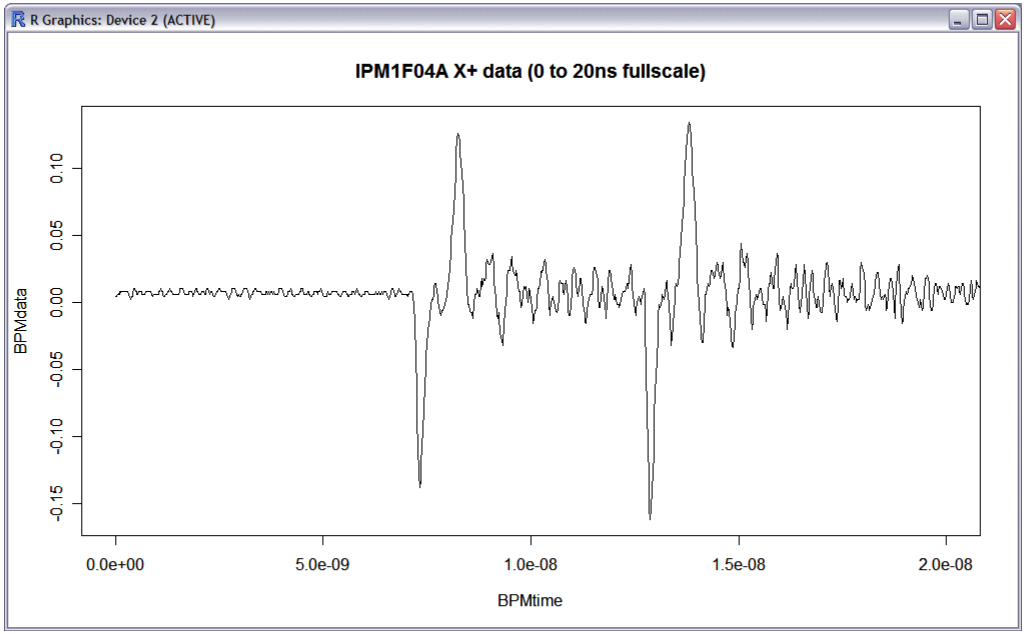
core of beam off center,
even though BLMs showed
edges were centered
(high energy tail)

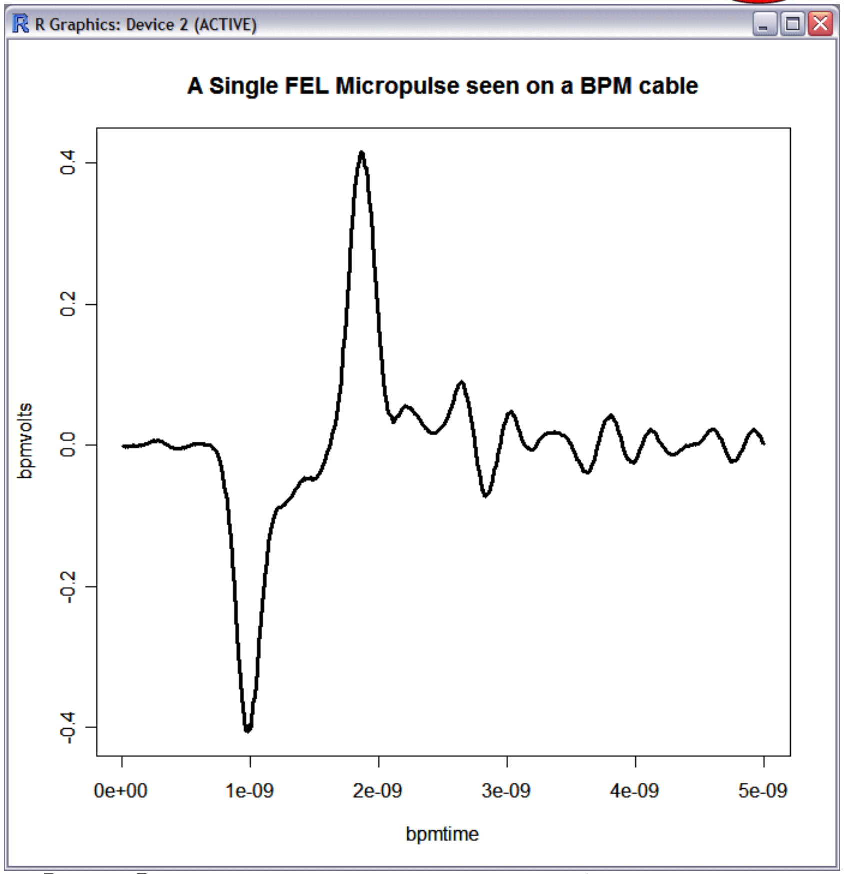


Example 2: Multipass Orbit Correction

- Energy of each pass differs at any point of linac
  - Orbit response to steering differs
- Need localized observation & correction
  - Multipass BPMs - for high-frequency CW bunch trains separated by ½ RF period...
- Example: JLab IR Upgrade: orbit bump on 1st pass of linac

BPM signals cancel pass-to-pass



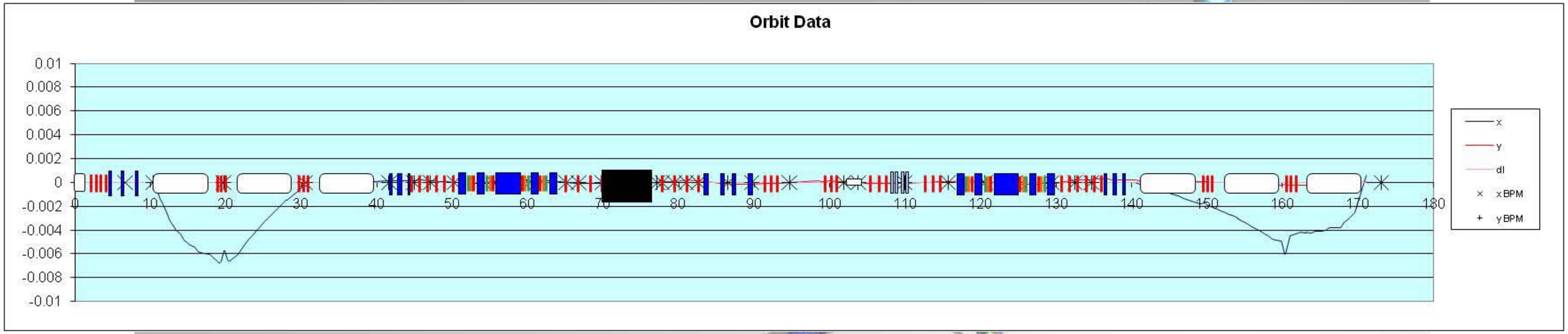


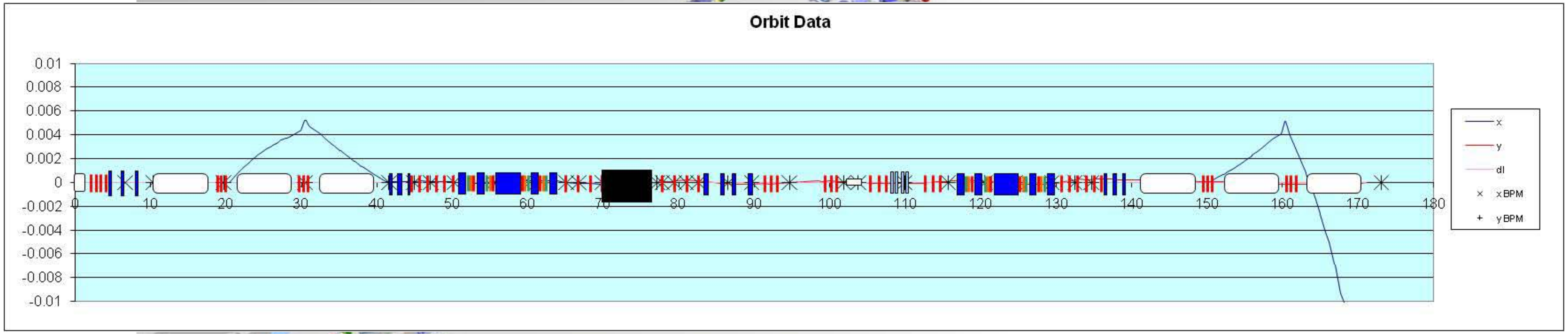
(from K. Jordan & probably P. Evtushenko via T. Powers)

System Layout

Requirements on phase space:

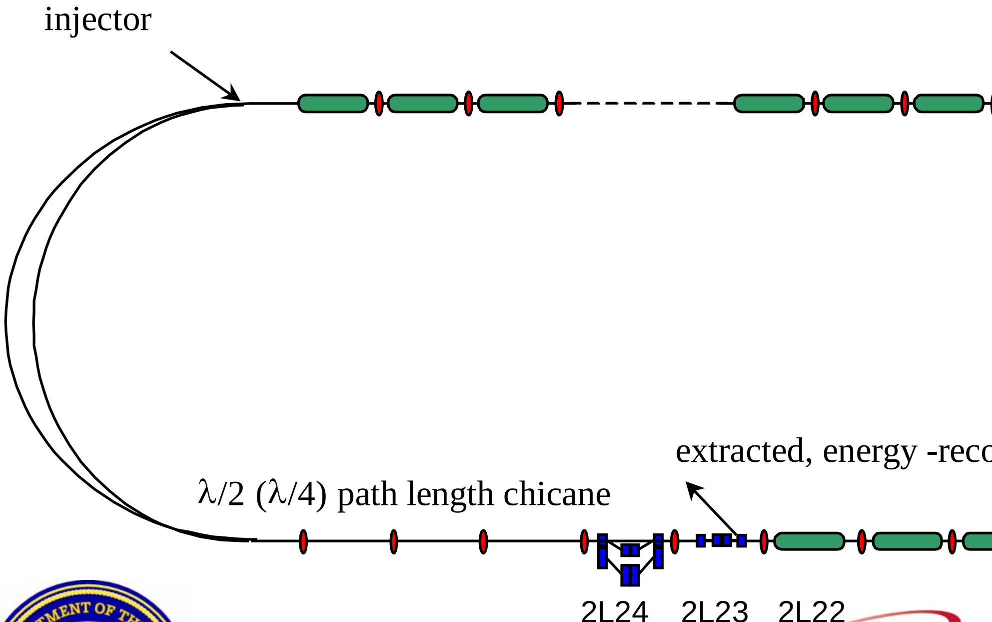
- high peak current (short bunch) at FEL





Multipass Orbit Correction – Common Transport

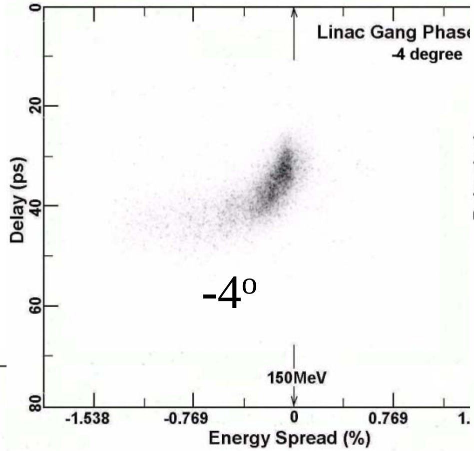
- “multiple beams” not limited to *linac* – some ERL geometries use single beamlines for multiple beams
  - E.g. CEBAF-ER

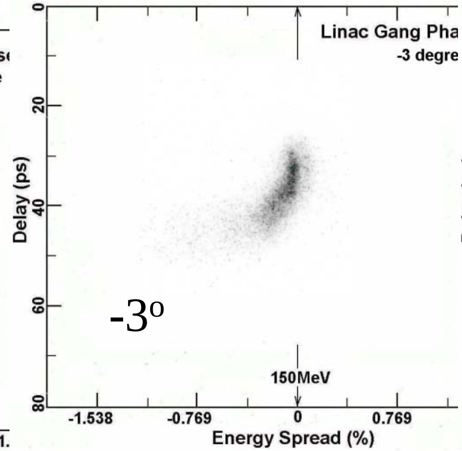


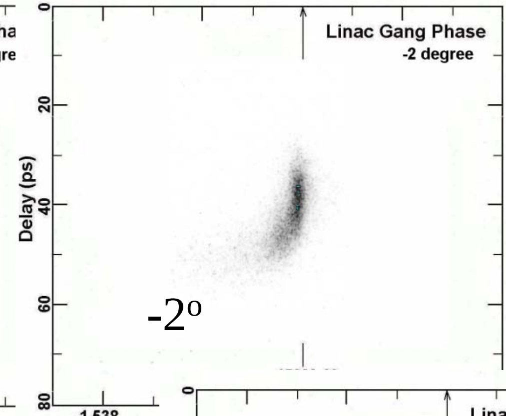
Example 3: Collective effects

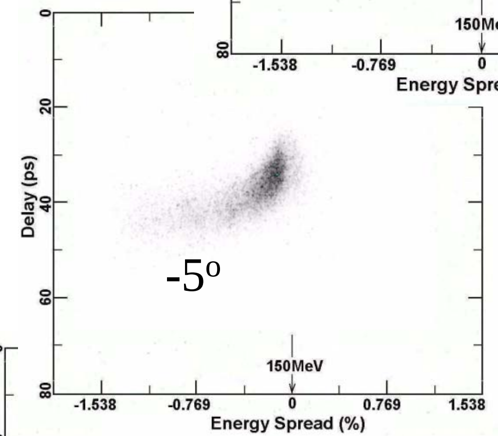
- ERLs live to generate high brightness, high power beams
- Collective effects are a "logical consequence" of that lifestyle
- JLab systems have been challenged by several effects, including
  - Longitudinal space charge (limited compressed bunch length)
  - BBU (limited current)
  - CSR (potential emittance degradation)
- Must be able to observe, characterize, quantify effects
  - e.g. power into HOMs for BBU
  - Disentangle source of inappropriate behavior
    - poor dispersion suppression vs. lattice aberration vs. coherent energy shift from CSR…

LSC: Streak Camera Data, IR Upgrade

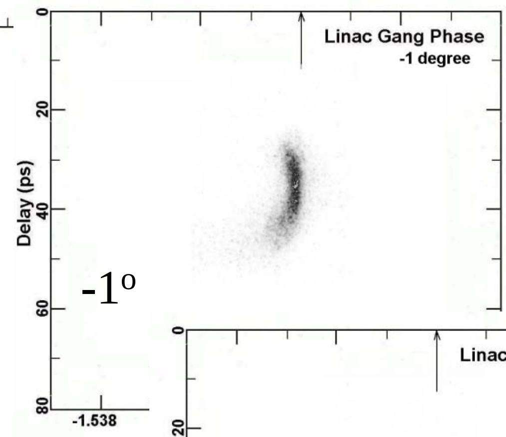


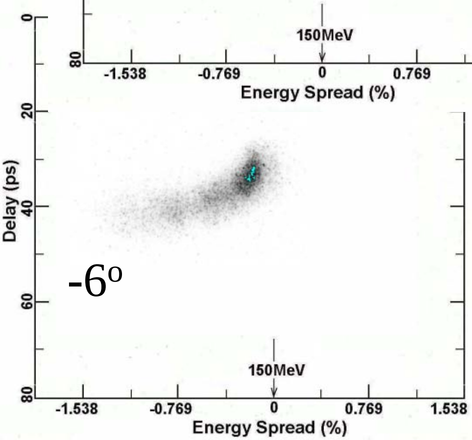




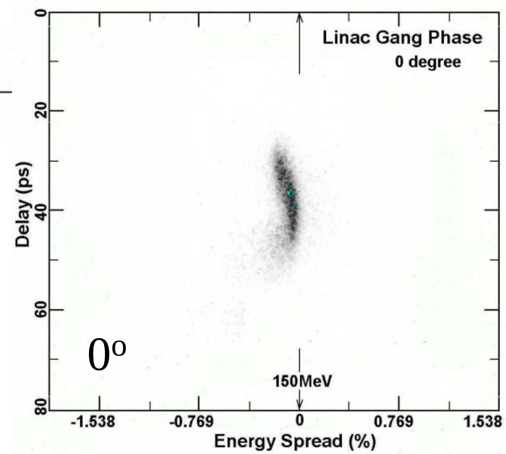


(t,E) vs. linac phase after crest

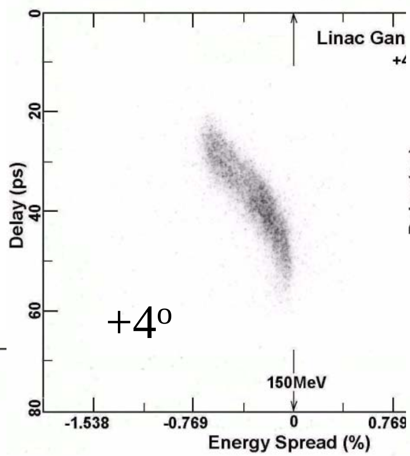


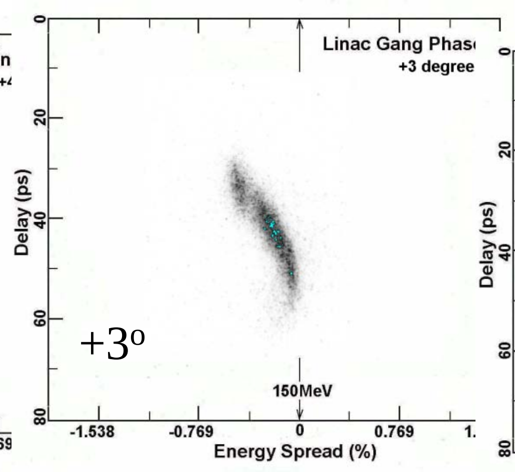


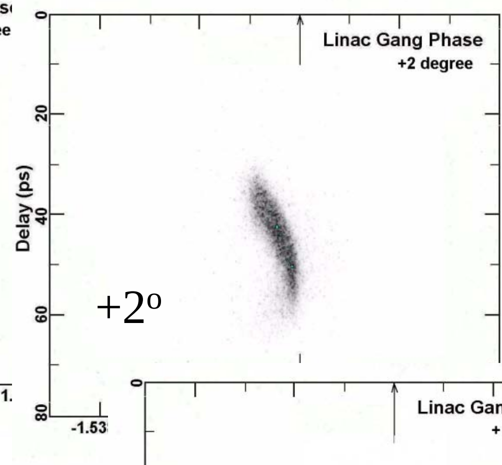
(data by S. Zhang, v.g. from C. Tennant)

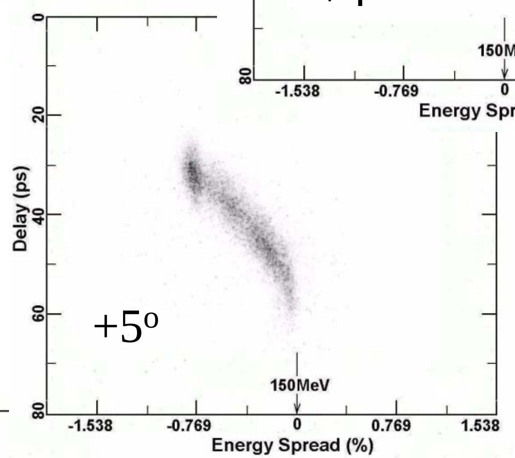


IR Upgrade, cont.





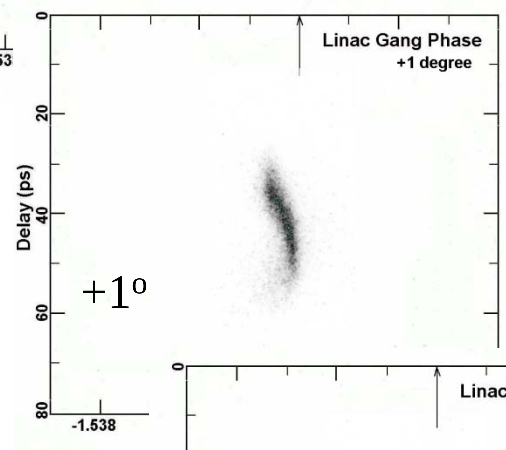


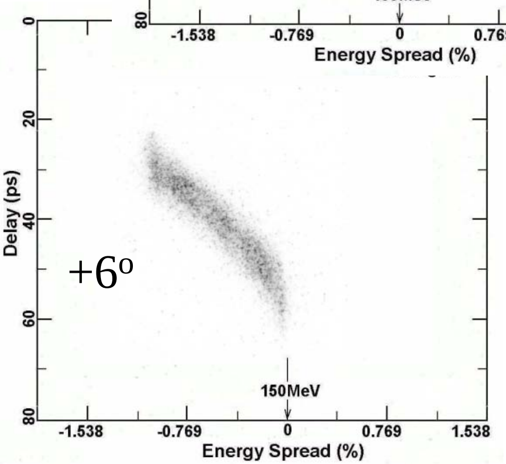


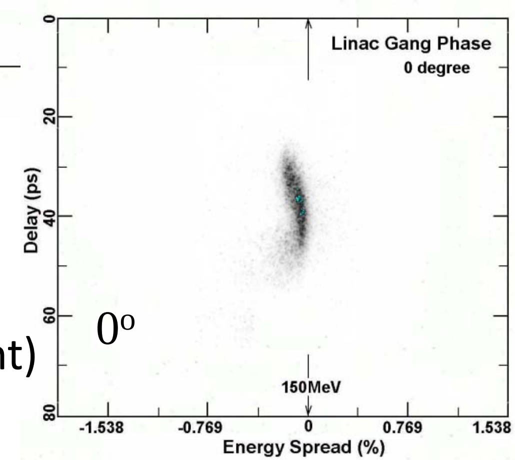
(t,E) vs. linac phase, before crest

asymmetry between + and - show effect of longitudinal space charge after 10 MeV

(data by S. Zhang, v.g. from C. Tennant)



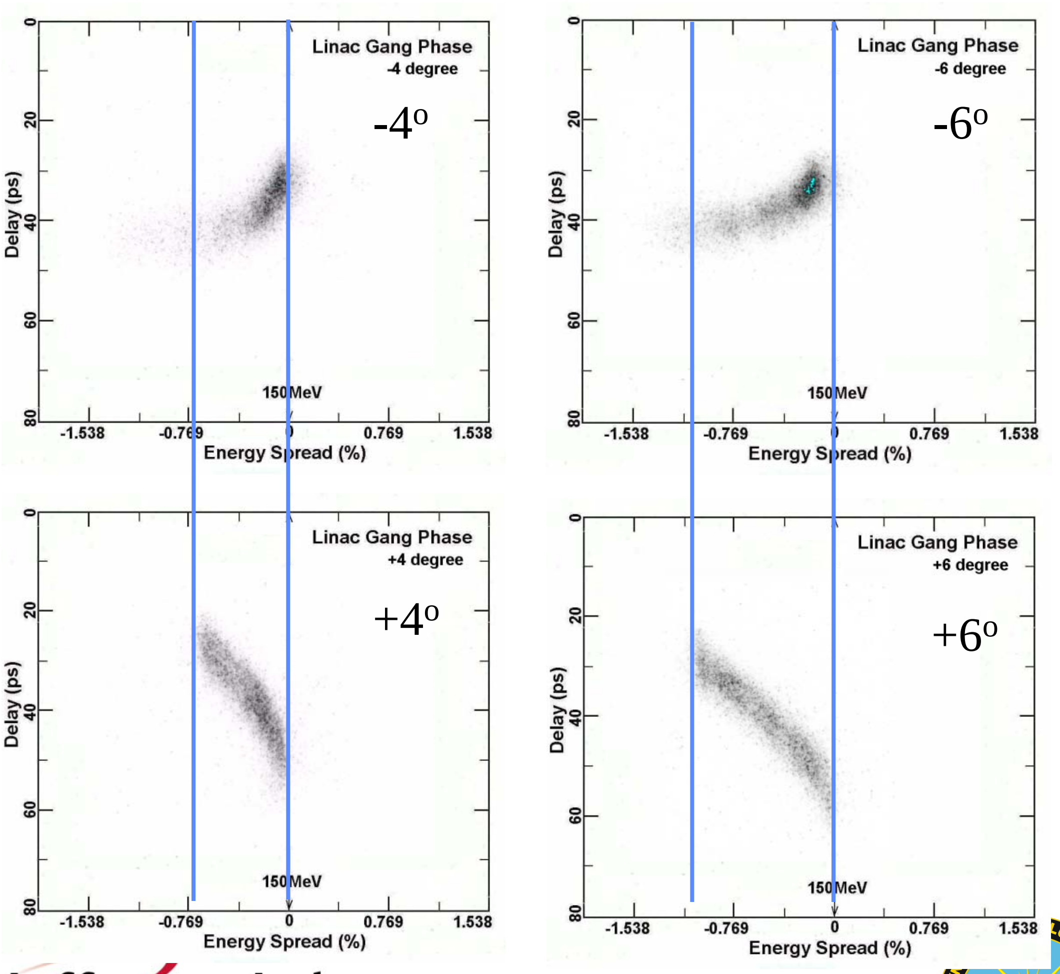


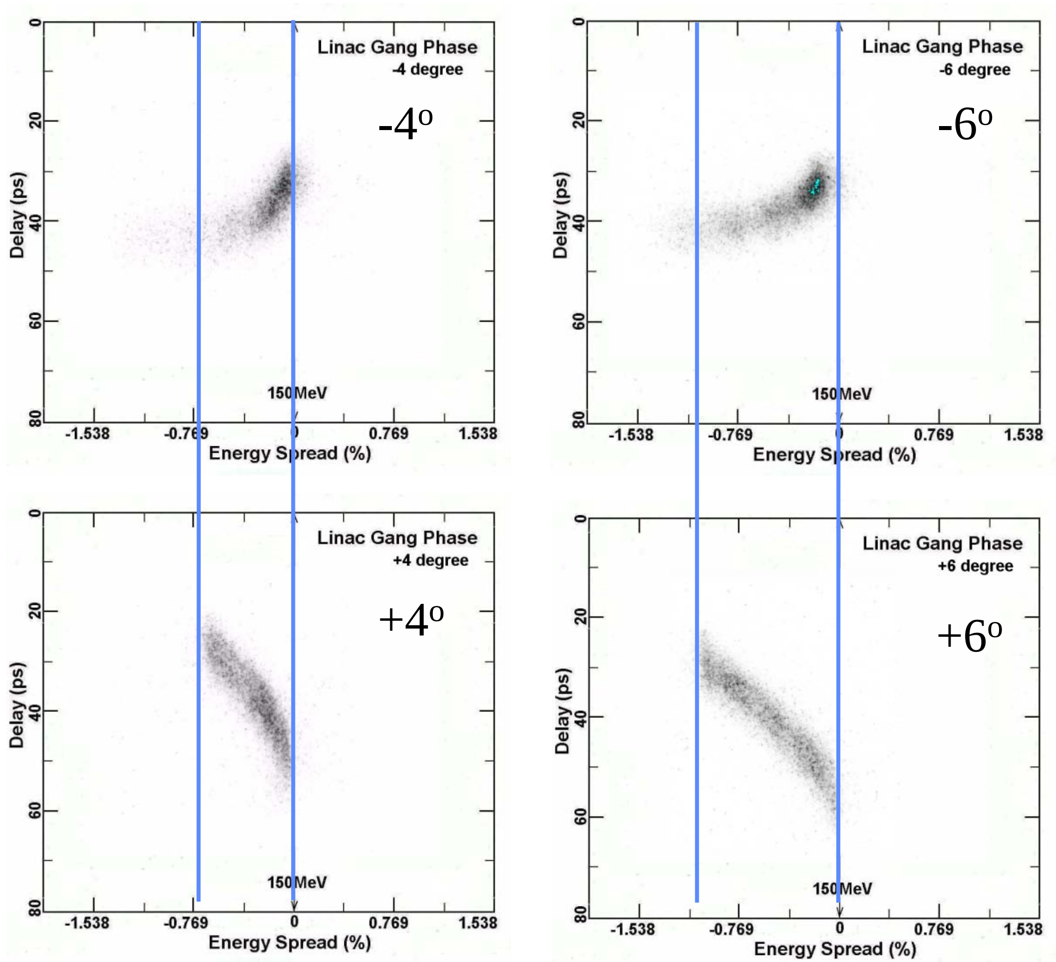


±4 and ±6 degrees off crest

- "+" on rising, "-" on falling part of waveform
- L_{bunch} consistent with dp/p and M_{56} from linac to observation point
- dp/p(-)>dp/p(+)
- on "-" side there are electrons at energy *higher* than max out of linac
- distribution evolves "hot spot" on "-" side (kinematic debunching, beam slides up toward crest…)

=> *LSC a concern…*




Linac Gang Phase
-4 degree
-4°
Linac Gang Phase
-6 degree
-6°
Linac Gang Phase
+4 degree
+4°
Linac Gang Phase
+6 degree
+6°
150MeV
Delay (ps)
Energy Spread (%)
-1.538
-0.769
0
0.769
1.538
0
20
40
60
80

BBU

- Beam initially unstable at 2.5 mA
- After considerable effort, stability is usually a nonissue
  - A bad setup can have ½ mA threshold
  - A good setup can be absolutely stable (skew quad rotator)
  - Threshold sometimes lasing dependent (laser on>laser off) – but with bad match…
- Propagating modes *can* be an issue (well, a nusiance) – even at our low beam powers
  - High frequency from beam talks to cold window temp. monitors in waveguide; trips us off (CWWT)
  - Typically run masked, monitor values & determine response to beam is prompt, not thermal…
  - Good example of "power going to the wrong place at the wrong time"
- Needed good lattice diagnostics to control phase advance, betatron match, manage coupling & stabilize instability

BBU video courtesy C. Tennant

Click the picture if a movie does not run automatically

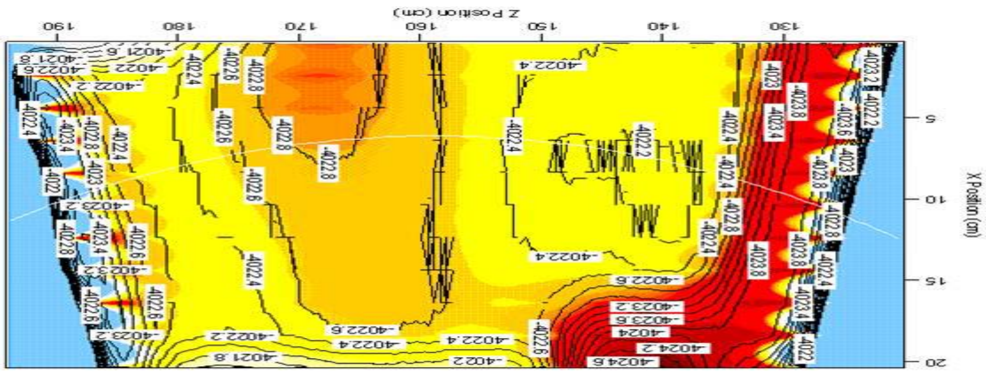
CSR/LSC during recirculation/compression (with a side of THz heating…)

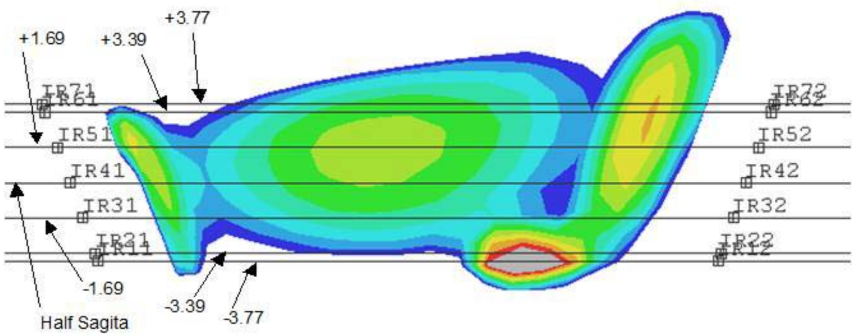
- 135 pC/0.35 psec bunch ~ 400 A peak current
- CSR/LSC effects evident
  - Enhanced by parasitic compressions (Bates bend)
  - Initial operation irradiated outcoupler – THz heating (next slide…)
  - Use CSR enhancement at tuning cue

CSR video courtesy K. Jordan

Click the picture if a movie does not run automatically.

Example 4: Magnet Field Quality Issues





Magnet field quality excellent

- e.g. GX at 145 MeV/c
  - Top: measured field
  - Bottom: design calculation

    (contours @ $1/2\mathrm{x}10^{-4}$)

  (Thanks to George Biallas, Tom Hiatt & the magnet measurement facility staff, Chris Tennant, and Tom Schultheiss)

Reproducibility:

- Large magnets – great
- Small magnets – bad (consumes a lot of tune time)

ERL Field Quality Requirement

- $\Delta B \Rightarrow \delta x' = \Delta Bl/B\rho = (\Delta B/B)\ \theta$ (dipole)
- $\delta x' \Rightarrow \delta l = M_{52}\ \delta x'$
- $\delta l \Rightarrow \Delta E_{dump} = E_{linac} \sin \phi_0\ (2\pi\ \delta l/\lambda_{RF})$

  $= E_{linac} \sin \phi_0\ (2\pi\ M_{52}(\Delta B/B)\theta/\lambda_{RF})$
- "Field quality" $\Delta B/B$ needed to meet budgeted ΔE_{dump} must improve (get smaller) for longer linac (higher E_{linac}), shorter λ_{RF}, larger dispersion ($M_{52} = M_{22}M_{16} - M_{12}M_{26}$)
- must
  - make better magnets
  - use lower energy linac
  - reduce M_{52} (dispersion)
  - provide means of compensation (diagnostics & correction knobs)

Put ANOTHER Way…

- ⊗B ⇒ ™x'=⊗Bl/B〉~ ⊗Bl/(33.3564 kg-m/GeV * E_{linac}) (error integral)
- ™l ⇒ ⊗E_{dump} = sin √$_0$ (2π M_{52}(⊗Bl/33.3564 kg-m)/⎿$_{RF}$ (GeV)
- "Error field integral" ⊗Bl is *independent* of linac length/energy gain
  - tolerable relative field error falls as energy (required field) goes up
- Numbers for Jlab FEL driver:
  - ⊗E_{dump} ~ 3400 MeV * (⊗B/B)

    (which we see: we have 10^{-4} and see few 100 keV)
  - ⊗E_{dump} ~ 1.6 keV/g-cm * (⊗Bl)

Implications for Diagnostics

What does this experience imply about diagnostic requirements?

- Need lots of longitudinal/time of flight/bunch length/energy diagnostics
  - longitudinal matching, correction of field errors
- Must measure positions of multiple beams in common transport in an operationally noninvasive manner
  - beams out of phase: signals cancel in resonant structures like those used for some diagnostics
- Must diagnose ***lattice*** and ***beam*** separately

More bad news…

- Lattice need not be betatron stable, in fact there's not even a closed orbit
  - Can't just "ping" beam and look at sidebands – no "tune"
  - Can't look at tune shift as function of quad strength to get "the" beta function: *there is no unique beta function*
- Must count oscillations to get phase advance, measure transfer matrix elements
  - precision limited by resolution of BPMs, tolerable orbit excursion
  - also limited by magnet field quality, lattice nonlinearities, collective effects like CSR – have to be able to capture signatures of each phenomenon
    - Example: JLab IR Upgrade FEL – nonlinear lattice aberrations look like dispersion errors; CSR radiative effects look like dispersion errors – so how to disentangle?
      - Aberrations – driven by orbit errors/steer carefully; CSR – charge dependent effect
- Need good phase space tomography to characterize and manage beam – having separately characterized and managed the lattice….

Diagnostics Wish List

Comprehensive review by P. Evtushenko, ERL2009 & additional info this workshop

- No vacuum chamber. If its not a BPM, it's a profile monitor, SR port, cavity monitor…
- Basic issues
  - Resolution of phase advance & lattice functions limited by # diagnostics
    - Storage rings – measure over many turns, give, in effect, many iterates of datataking
    - ERLs – at most a few turns – limited resolution
  - Resolution of beam properties limited by # diagnostics (multimonitor), dynamic operating range of ERL (can't run full power beam into an intercepting diagnostic, can't change focusing dramatically for a quad scan/tomographic measurement with high power beam…)
  - Need to assure excellent beam stability & synchronization

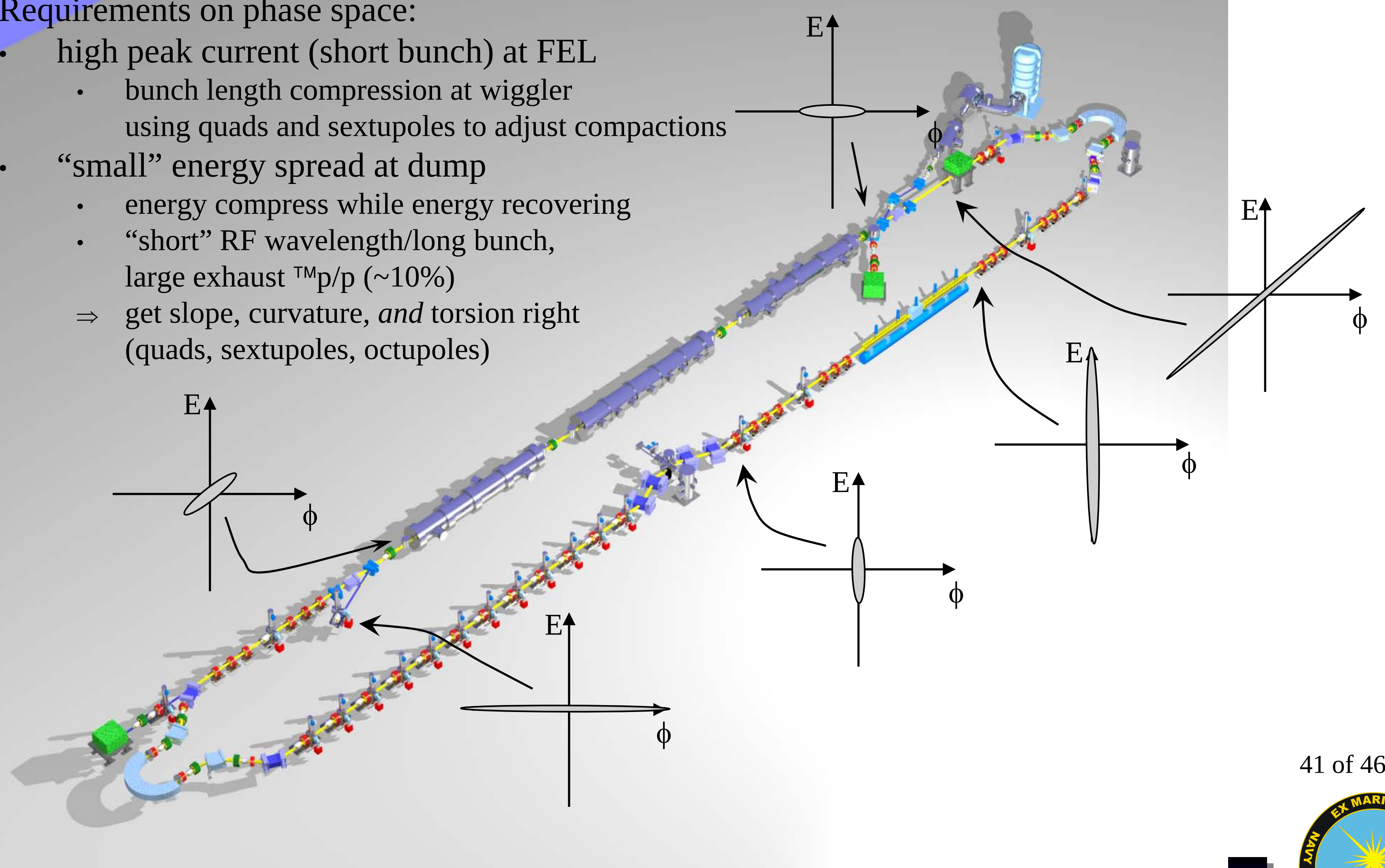
Specific Devices That Have Been/Would Be Useful

- High resolution multipass BPMs working over broad dynamic range (μAs to 100s mA) and with flexible beam timing (single shot->CW)
- Beam time of flight, transfer function (M_{55}, BCM)
- Tomography: transverse and longitudinal
  - High resolution/ large dynamic range profile monitors
  - Bunch length – Martin-Puplett interferometer; THz spectrometer
- Halo monitor
- Streak camera
- Means of monitoring beam noise/stability
  - P. Evtushenko, BIW2008
- SYNCHRONIZATION (esp. FELs) & STABILITY (esp. light source ERLs)
  - Beam noise

Longitudinal Matching Scenario

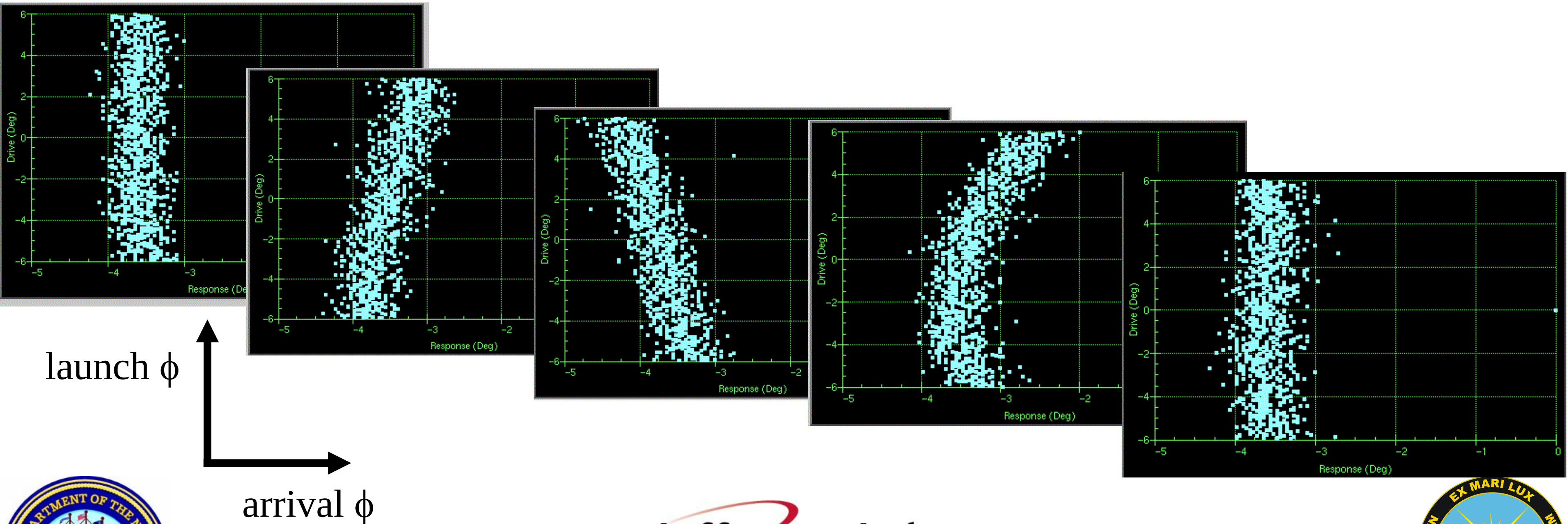
Requirements on phase space:

- high peak current (short bunch) at FEL
  - bunch length compression at wiggler
    using quads and sextupoles to adjust compactions
- “small” energy spread at dump
  - energy compress while energy recovering
  - “short” RF wavelength/long bunch,
    large exhaust ™p/p (~10%)
  - ⇒ get slope, curvature, *and* torsion right
    (quads, sextupoles, octupoles)

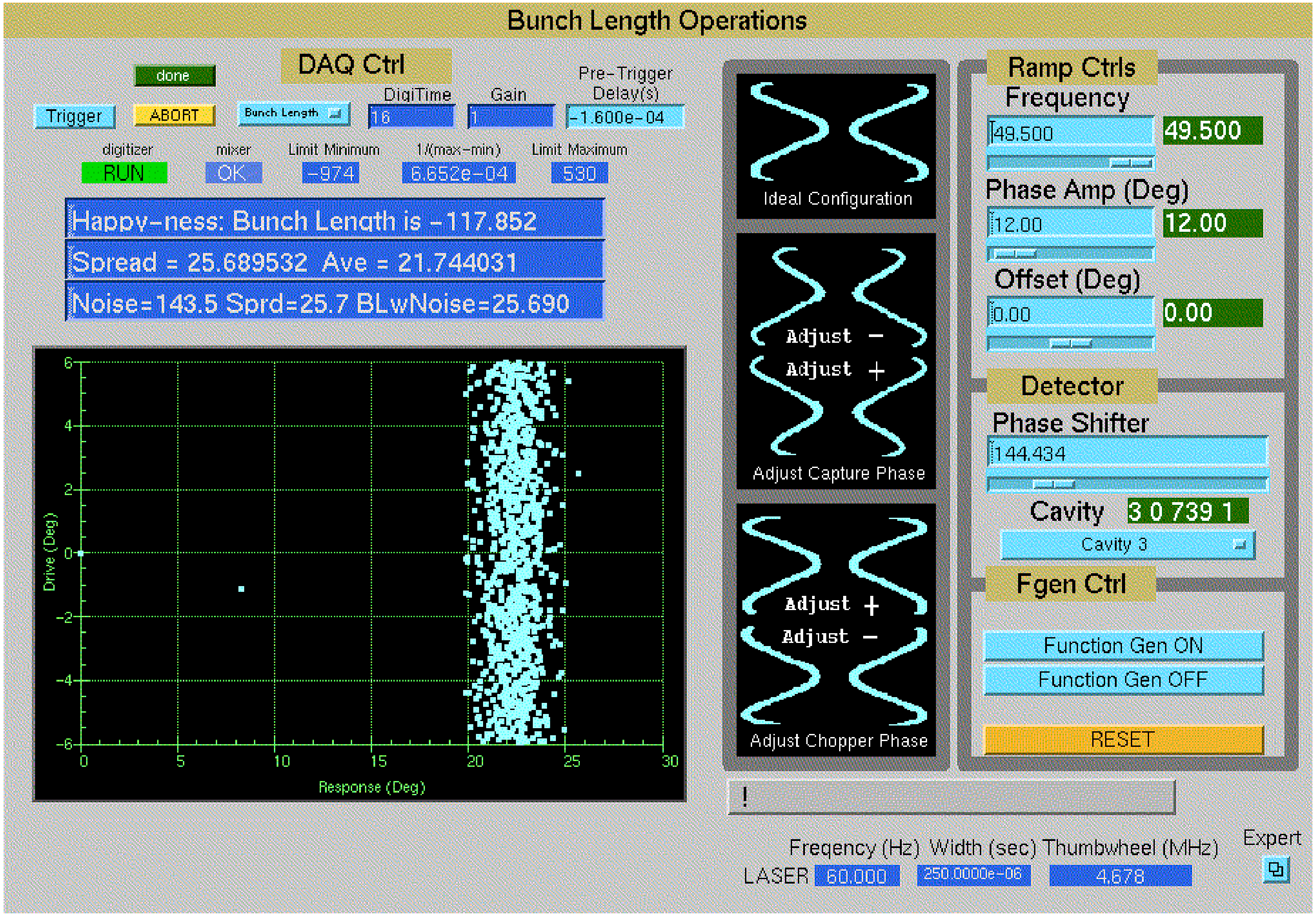


Nonlinearity Control Validated by Transport Measurement

- Drop inner sextupoles to 12726 g-cm and trim quads to -215 g (figure 1)
- figure 2 has trim quads at -185 g with same sextupoles
- figure 3 has -245 g
- figure 4 has quads at -215, but sextupoles 3000 g below design, at 10726 g-cm
- figure 5 is where we left it: trim quads -215 g sextupoles at 12726 g-cm



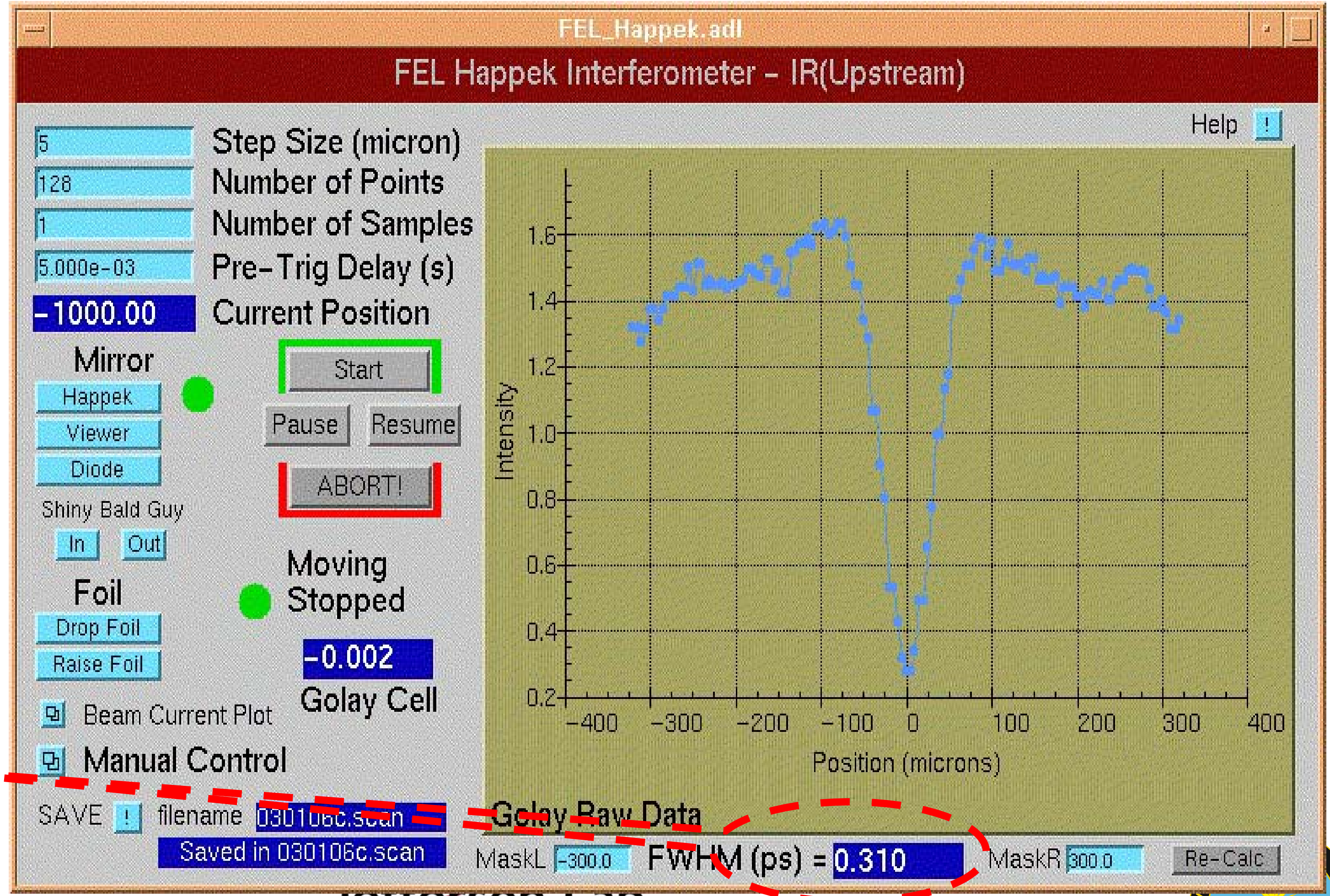
Injector to Wiggler Transport



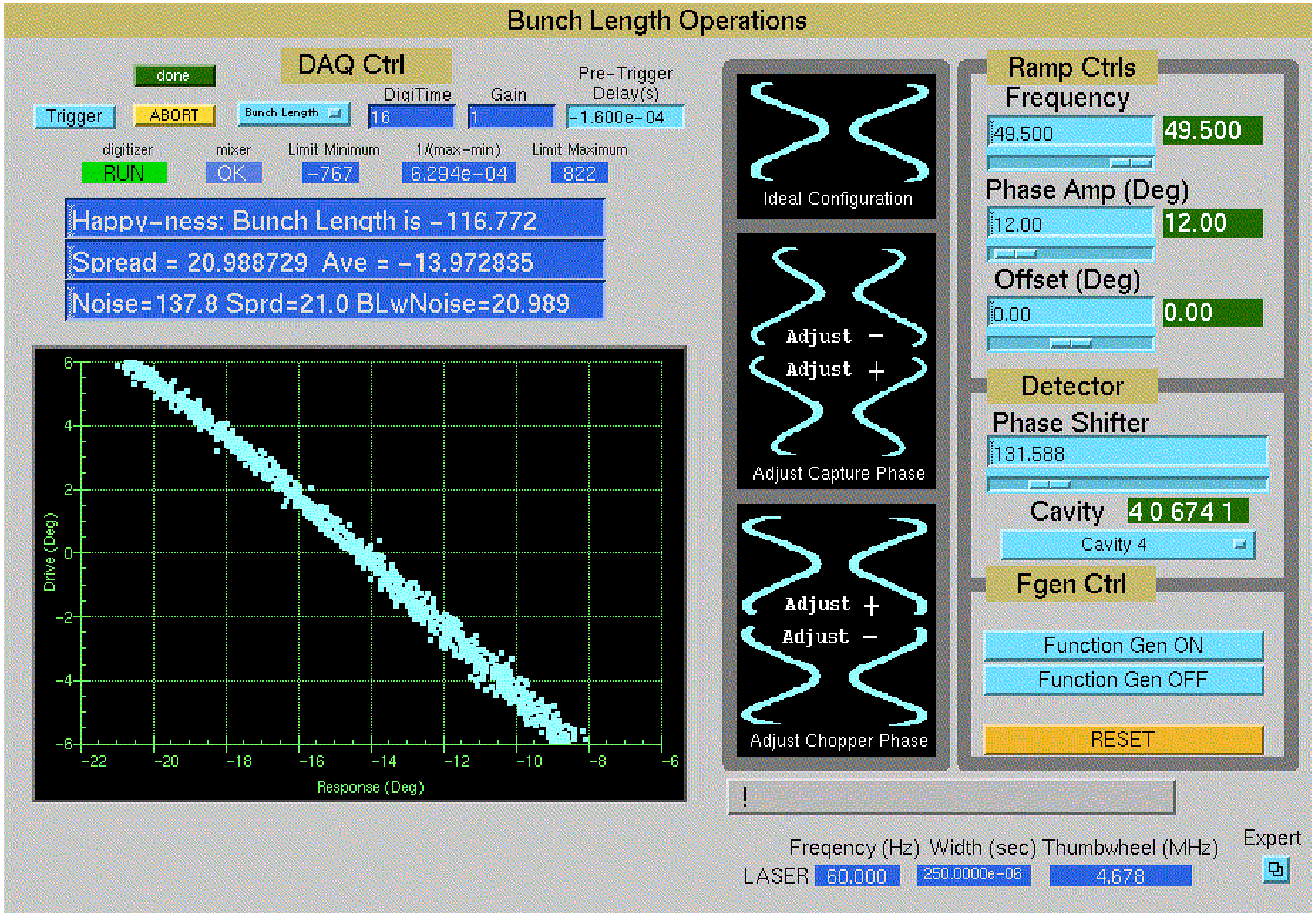
If you do it right linac produces stable ultrashort pulses

Can regularly achieve 300 fs FWHM electron pulses

~150 fsec rms



Injector to Reinjection Transport



Jefferson Lab

Thomas Jefferson National Accelerator Facility

Distribution State A

Conclusions

- ERLs are a novel machine architecture with great potential to provide very bright, high power beams…

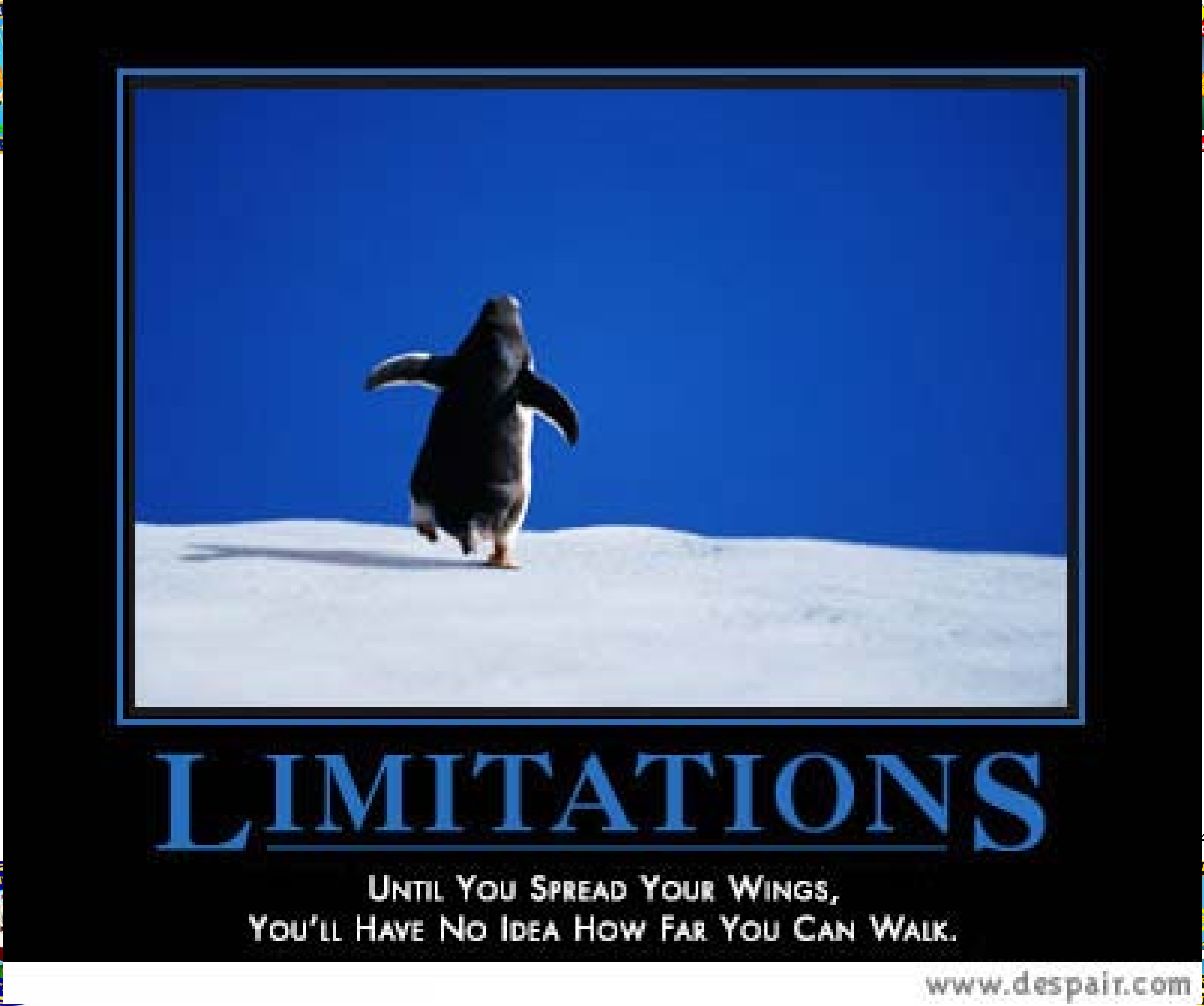
  at the cost of numerous beam dynamic and operational challenges

- Extensive instrumentation and sophisticated control **absolutely necessary** for successful operation of the next generation of machines

  must design ERL I&C systems with awareness of the idiosyncratic nature of these systems

"Begin with the end in mind"

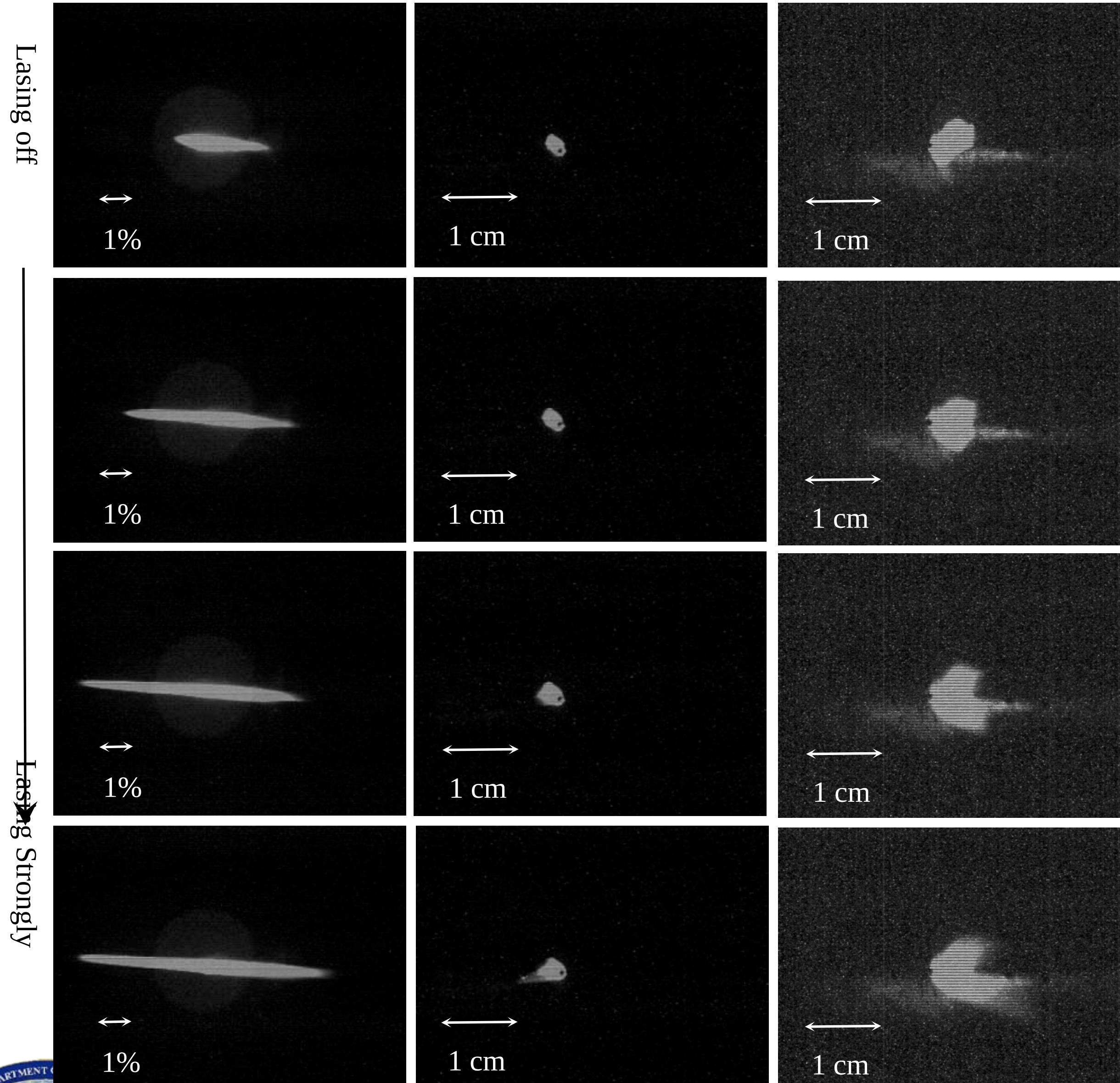
Acknowledgements: Funding by DoE, ONR, JTO, work by Jlab collegues!


LIMITATIONS
UNTIL YOU SPREAD YOUR WINGS,
YOU'LL HAVE NO IDEA HOW FAR YOU CAN WALK.
www.despair.com

Longitudinal matching

BACKUP

Center of 180^o bend　Following arc　Middle of reinjection match

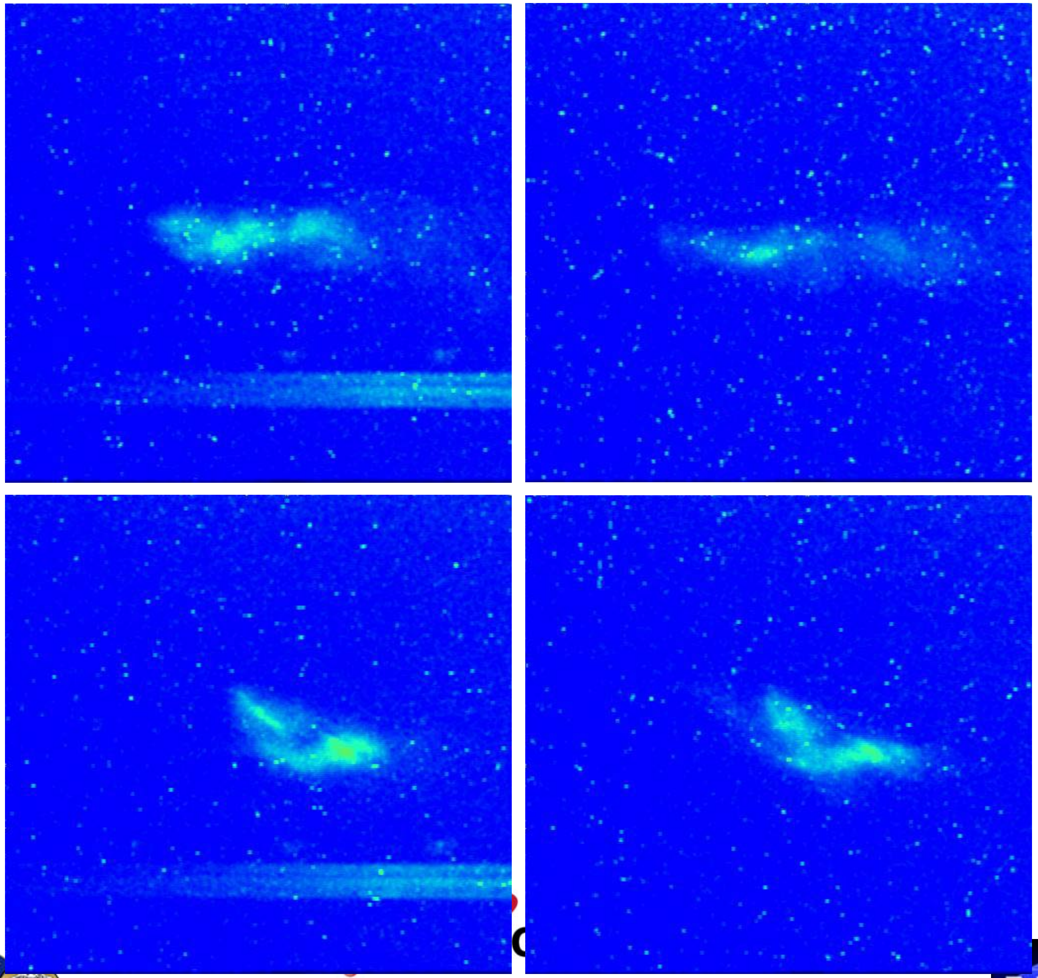


Why We Need the "Right" T_{566}

lasing off | lasing on

6-poles off

6-poles on

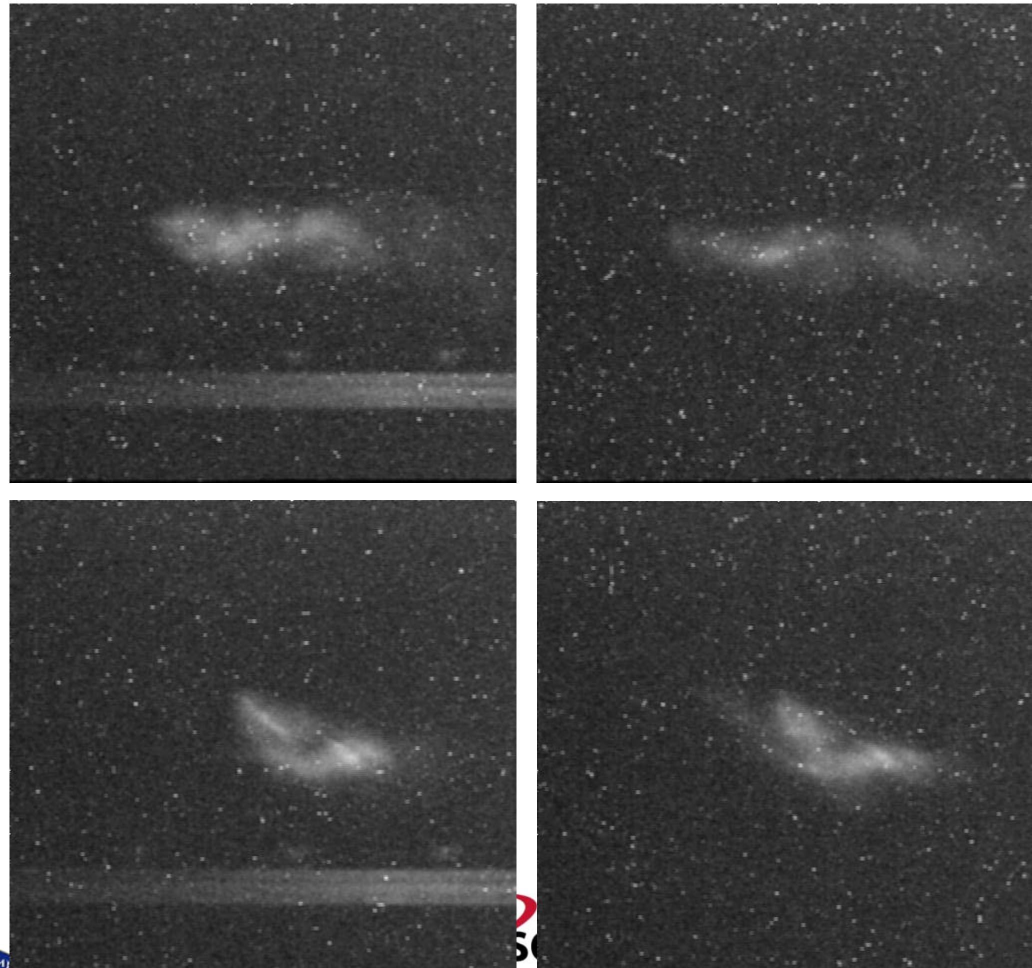


Why We Need the “Right” T_{566}

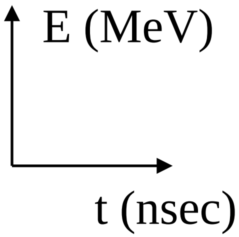
lasing off | lasing on

6-poles off

6-poles on

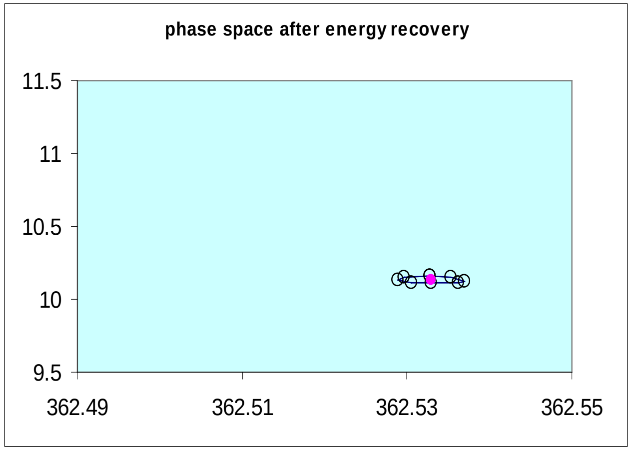


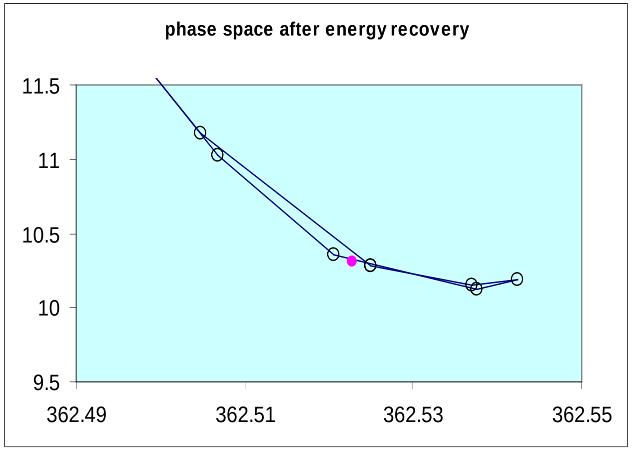
Phase space at 10 MeV Dump



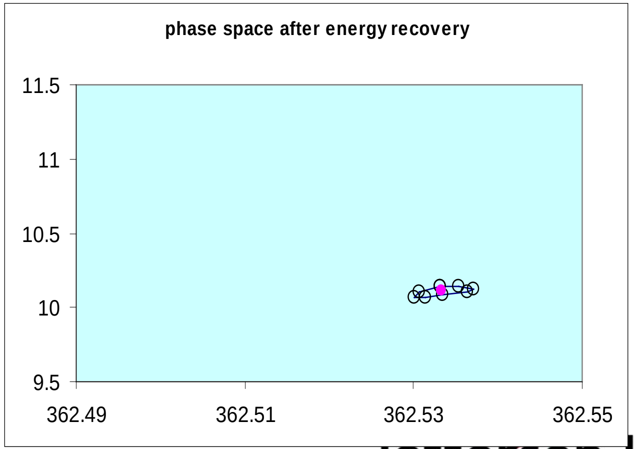
lasing off | lasing on

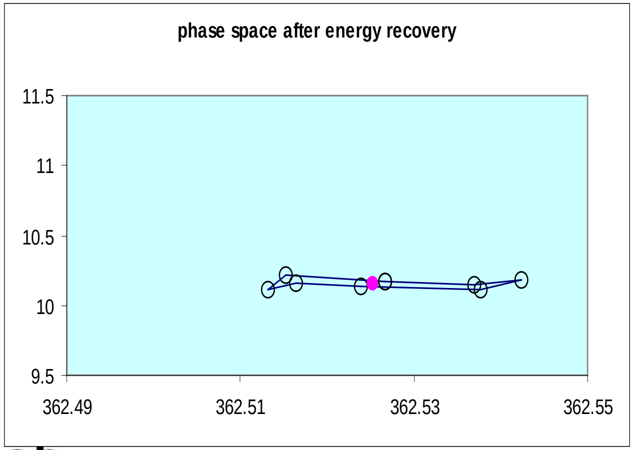
6-poles off





6-poles on





Energy Flow

- Energy conservation (bunch centroid):

$$E_{inj} + E_{acceleration} = E_{recovered} + E_{FEL} + E_{dump}$$

- ERLs are generally *not* operated with $E_{acceleration} = E_{recovered}$
  - point-to-parallel longitudinal image from wiggler to dump
    - Shifts beam in phase when E_{FEL} varies
    - Keeps $E_{recovered} + E_{FEL}$ constant, thus keeping E_{dump} constant
  - Energy deficit is made up by linac RF drive
    - Cavity stored energy utilized until RF system “catches up”
    - Need enough RF power/RF control bandwidth to deal with transients
- FEL power has to come from somewhere,
  - best it put it in through the linac (rather than the injector)
    - more RF windows, lower power/window

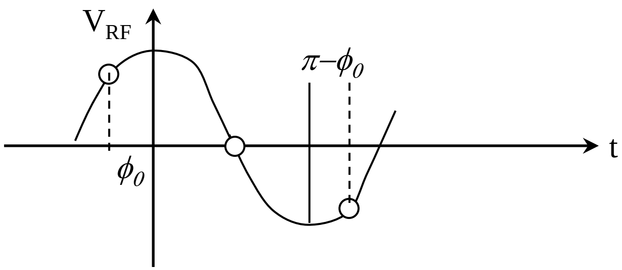
Multipass orbit correction

BACKUP

IR Demo Multipass Operation

- “Aside” during ongoing difference-orbit studies in Demo
- Best viewed as test of compaction management capabilities
  - Change path length from nominal mod($\lfloor_{RF}/2$) (energy recovery) to mod($\lfloor_{RF}/4$)
  - 2^{nd} pass coasts down linac at zero crossing rather than energy recovering
  - 3^{rd} pass energy recovers
  - Momentum spreads managed by off-crest acceleration, simultaneous bunch length compression at reinjection of 2^{nd} pass and energy compression at dump (end of 3^{rd} pass)

How Do We Run 3 Passes?

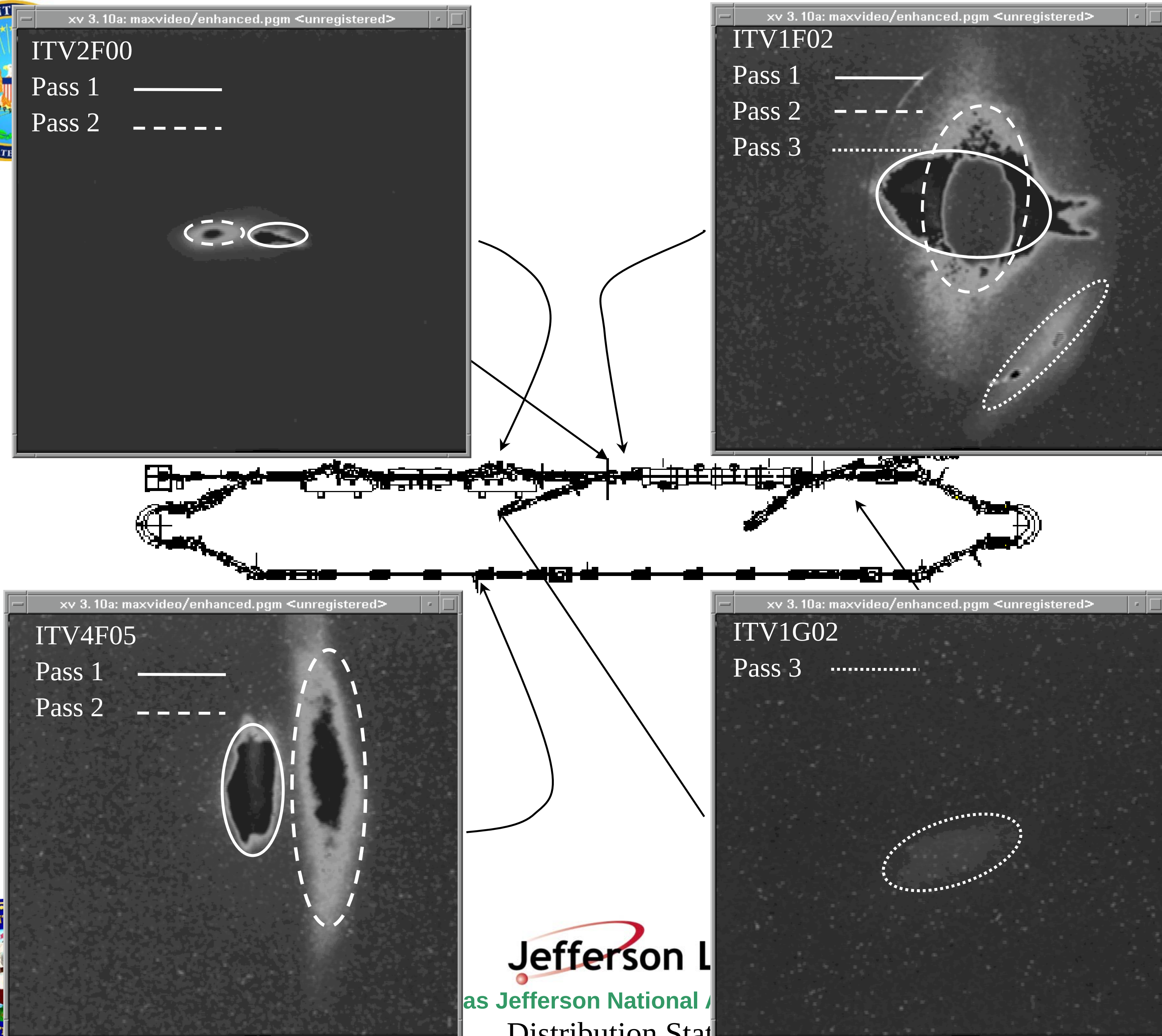


- Inject long, low momentum spread bunch
- Accelerate off-crest
- Recirculate to zero crossing ($\sim\lambda_{RF}/4$)
- Compress bunch length at reinjection, minimizing 2nd pass momentum spread

- 2nd pass through recirculator biases bunch to energy compress during energy recovery (slope of waveform, compaction are matched), *provided* you
- Energy recover *across* the trough (not 180^o out…)

D. Douglas and C. Tennant, "Three-Pass Operation of the IR Demo Driver", **JLAB-TN-01-043, 28 August 2001;**

D. Douglas, "Simultaneous Bunch Length and Energy Spread Compression During Recirculation of Multiple Passes in the IR Demo", JLAB-TN-01-048, 4 October 2001


xv 3.10a: maxvideo/enhanced.pgm <unregistered>
ITV2F00
Pass 1
Pass 2
xv 3.10a: maxvideo/enhanced.pgm <unregistered>
ITV1F02
Pass 1
Pass 2
Pass 3
xv 3.10a: maxvideo/enhanced.pgm <unregistered>
ITV4F05
Pass 1
Pass 2
xv 3.10a: maxvideo/enhanced.pgm <unregistered>
ITV1G02
Pass 3